Second Series *December, 1913* *Vol. II, No. 6*

THE

PHYSICAL REVIEW.

A POWERFUL RÖNTGEN RAY TUBE WITH A PURE ELECTRON DISCHARGE.

By W. D. Coolidge.

§ 1. Introduction.

In an earlier publication attention has been called[1] to the use of wrought tungsten for the anticathode, or target, of a Röntgen tube of the ordinary type. In the development of this target many different designs were made and mounted in tubes, and these tubes were operated on what was then the most powerful Röntgen apparatus on the market, a 10 K.W. transformer coupled to a mechanical rectifying device. The operation of tubes in this manner, to see how much energy it took to ruin the target, gave perhaps an unusual viewpoint. When, as a result of these experiments, a satisfactory form of target had been developed, the writer became interested in studying the remaining limitations in the tube. Some of these limitations are the following:

1. With low discharge currents the vacuum gradually improves, with a consequent increase in the penetrating power of the rays produced.

2. With high discharge currents there are very rapid vacuum changes, sometimes in one direction and sometimes in the other.

3. If a heavy discharge current is continued for more than a few seconds the target is heated to redness and then gives off so much gas that the tube may have to be reëxhausted.

4. If the temperature of the standard copper-backed target is allowed to get up to bright redness, a rapid deposition of metallic copper begins to take place on the bulb, continuing for some time after the cutting off of the current, owing to the very slow rate of cooling from such temperatures in the evacuated space.

5. Of the tubes tested, very many have failed from cracking of the

[1] Coolidge, Trans. Am. Inst. E. E., June, 1912, pp. 870–872.

glass, and this, with one exception, always at the same point; that is, in the zone around the cathode. In many cases there has first been chipping-out of the glass from the inner surface of the tube at this point.

6. The focal spot on the target in many tubes wanders about very rapidly.[1] In many cases where it does not show a tendency to wander, it will be found after a heavy discharge to have permanently changed its location.

7. While it is relatively easy to lower the tube resistance by means of the various gas regulators, it is a relatively slow matter to raise it much.

8. With very heavy discharges, the central portion of the usual massive aluminum cathode melts, and the molten globules so formed are shot right across the tube, flattening themselves out on the glass and sticking to it. When the melted area is small, no harm is done except that the curvature of the cathode at this point may be changed, and the focal spot may, in consequence, be moved.

9. No two tubes are exactly alike in their electrical characteristics.

10. The characteristics are in general far from ideal, in that the penetrating power of the Röntgen rays produced, changes with the magnitude of the discharge current.

11. When operated on a periodically intermittent current, even though it be of constant potential, the tube, of necessity, gives a very heterogeneous bundle of primary Röntgen rays, for the reason that the breakdown voltage of the tube is much higher than the running voltage.[2]

It was found that limitations 3 and 4 could be removed by the use of a massive all-tungsten (in place of the usual copper-backed) target. Such a target can be run continuously at intense white heat. Aside from eliminating the troubles incident to the use of copper, the all-tungsten target does not change the general characteristics of the tube.

An attempt was made to remove limitation 8, imposed by the low melting point of aluminum, by substituting for it a tungsten cathode of the same dimensions. Tubes made up in this way showed a behavior entirely different from that of the ordinary tube. They would have been absolutely hopeless from the standpoint of a practical radiographer. They were like the ordinary Röntgen tube which is in the condition which the radiographer describes as "cranky." Upon passing a discharge current of any magnitude through the tube, the resistance would quickly rise to a point where, even with an impressed potential difference of 100,000 volts, no further discharge would pass. The tube could be restored to its original condition by the liberation of gas from the vacuum

[1] In radiographic work, movement of the focal spot during an exposure is of course detrimental to good definition.

[2] See F. Dessauer, Phys. Zeitschr., *14*, pp. 246–247 (1913).

regulator. The phenomena would repeat themselves as often as one cared to make the experiment. Continuous operation for even a few seconds seemed out of the question. It finally developed, however, that with the adoption of the following expedient, the situation changed. Gas was admitted from the regulator and a discharge passed through the tube. As soon as the resistance had risen, more gas was admitted and the tube was again excited. These operations were repeated as rapidly as possible. With each excitation of the tube, the cathode became hotter. There was evidently the same focusing of the positive ions bombarding the cathode as there was of the electrons at the anticathode, for there was a similar localization of heat at the two electrodes. A little conical depression which formed at the center of the cathode showed that, with the vacuum range employed, the positive ion bombardment was, at least mainly, confined to an area only about 2 mm. in diameter. As soon as the cathode had become heated to bright incandescence,[1] the behavior of the tube changed, and it could then be operated continuously for at least several minutes. Upon interrupting the discharge for a short time, and so allowing the cathode to cool, the "cranky" condition returned, and the tube could again be operated continuously only after repeating the procedure outlined above.

Tubes like the above with tungsten cathodes showed, upon operation, a rapid blackening of the bulb. The deposit proved to be metallic tungsten. The conical depression which invariably formed at the center of the cathode seemed to indicate that this was the source of the deposit, the disintegration of the metal at this point being doubtless due to the mechanical action of the positive ions which bombard it.

The extreme instability of vacuum attendant upon the use of a tungsten cathode in what was otherwise a standard Röntgen tube, called attention very forcibly to the part which is played by gases in the ordinary aluminum cathode. (The tungsten cathodes used must have been, from their method of manufacture, relatively very free from gas.)

A consideration of the above-mentioned limitations showed that they were for the most part incident to the use of gas and that they could therefore be made to disappear if a tube could be operated with a very

[1] The magnitude of the heating effect at the cathode was much greater with tungsten than it is with aluminum cathodes. In one case the cathode and the anode, which functioned also as anticathode, were both made of tungsten, exactly alike in size and shape and symmetrically placed in the tube (concave faces towards each other). On continuous operation, both ran at white heat, and, as nearly as the eye could judge, at the same temperature. Where aluminum is used as the cathode material, much less heat is developed in the cathode than in the target. Willey (Vernon J. Willey, Archives of the Roentgen Ray, XII., p. 250, 1908) finds in tubes of the ordinary type that 75 to 85 per cent. of the total heat evolution in the tube, inclusive of the glass walls, takes place at the target.

much higher vacuum. In this case the electrons would have to be supplied in some other way than by bombardment of the cathode by positive ions.

Richardson[1] and others had shown that electrons might be produced by simply heating the cathode. But the values of the thermionic currents obtained by different observers had varied between wide limits, so much so as to suggest that a Röntgen tube based upon this principle might be as unstable in resistance as is the standard tube. Moreover, the fact that the substances usually worked with, platinum and carbon, are so difficult to completely free from gas, suggested strongly that with the cleaner conditions (greater freedom from gas) that could be realized by the use of tungsten, the thermionic currents might cease altogether.[2] Some experiments of Dr. Irving Langmuir,[3] however, on the thermionic currents between two tungsten filaments in a highly evacuated space, were very reassuring. According to his observations, after a certain high degree of exhaustion had been reached, the thermionic currents increased, up to a certain limiting value, as the tube became freer and freer from gas.

The idea of using a hot cathode in a Röntgen tube was not new, but, so far as the writer could learn, the principle had never been successfully applied in a vacuum good enough so that positive ions did not play an essential rôle.

Wehnelt and Trenkle[4] had used a hot lime cathode for the production of very soft Röntgen rays, working with voltages from 400 to 1,000. Wehnelt, in another article, describes the use of his lime cathode in a Braun tube, and here he says that it is not advisible to employ more than 1,000 volts, as otherwise cathode rays come off from that part of the platinum which is bare, giving bad disintegration.

The Röntgen rays produced by voltages as low as 1,000 are of course too "soft" for the ordinary applications.

Lilienfeld and Rosenthal[5] had described a Röntgen tube whose penetrating power is, they say, independent of vacuum. Their main alu-

[1] Proc. Camb. Phil. Soc., XI., 286 (1902); Proc. Roy. Soc., LXXI, pp. 415–418 (1903).

[2] See Goldstein, Ann. der Physik, *24*, p. 91, 1885. He finds that platinum must be heated almost to its melting point to give an appreciable thermionic current. Also see H. A. Wilson, Proc. Roy. Soc., *72*, pp. 272–276 (1903). He concludes with the following statement: "It is probable that a pure platinum wire heated in a perfect vacuum would not discharge any electricity at all, either positive or negative, to an extent appreciable on a galvanometer."

[3] This work is just being published.

[4] A. Wehnelt and W. Trenkle, Sitzungsber. d. Phys.-Medic. Soc. in Erlangen, *37*, 312–315 (1905).

[5] J. E. Lilienfeld and W. J. Rosenthal, Fortschritte auf dem Gebiete der Röntgenstrahlen, *18*, 256–263 (1912).

minum cathode and their platinum anticathode are shaped and located like the electrodes in the ordinary Röntgen tube. Besides these they have an anode and an auxiliary hot cathode. Current from a low voltage source passes from the hot cathode to the anode and this current furnishes the positive ions which by their bombardment of the main cathode liberate electrons from it. Their tube is dependent for its operation on the presence of positive ions, for without these there is no means provided for getting electrons out from the main, aluminum, cathode. Lilienfeld concludes from his extended experiments in tube exhaustion that the complete removal of all gas from tube and electrodes would not do away with positive ions. There would according to this view be no such thing as a pure electron discharge. Lilienfeld's work in exhausting the gas from the tube itself and from the glass seems to have been excellent, but according to the experience of the writer, his electrodes were not sufficiently freed from gas to justify the conclusions drawn. Working even with tungsten electrodes in a tube so designed that the electrodes could be heated in place to very high temperatures, the writer has had the positive ion effects persist for hours, disappearing completely however as the electrodes become sufficiently freed from gas.

The work of Dr. Langmuir had shown that a hot tungsten cathode in a very high vacuum could be made to continuously yield a supply of electrons at a rate determined by the temperature.

Further work showed that very high voltages, up to at least 100,000, in no wise affect this rate of emission. For application to the fields of radiography and fluoroscopy, it was necessary to develop a satisfactory method of focusing. And, finally, the large amounts of energy transformed into heat in a Röntgen tube render imperative the use of a very heavy target, and this made it necessary to develop methods for sufficiently freeing from gas large masses of metal.

The result of efforts in this direction has been entirely successful, and tubes have been made, based upon this principle, which are free from all of the above-mentioned limitations. This is of particular physical interest because it brings all of the peculiarities of the Röntgen ray tube into accord with the modern conception of electronic conduction and gas molecule decomposition In the following, it will be sufficient to describe one type (a focusing tube) and its characteristics, leaving for later papers the description of other types.

§ 2. General Description of the New Type of Tube.

The structural features of the new tube which differ from those of the ordinary type are the following:

The pressure, instead of being, as in the ordinary tube, a few microns, is as low as it has been possible to make it, that is, not more than a few hundredths of a micron.

The cathode consists of a body which can be electrically heated (such as a tungsten or tantalum filament) and, suitably located with reference to this portion, an electrically conducting ring or cylinder, consisting preferably of molybdenum or tungsten or other refractory metal. The ring or cylinder is connected either to the heated portion of the cathode, or to an external source of current by means of which its potential may be brought to any desired value with respect to the heated portion. The heated portion of the cathode serves as the source of electrons, while the ring or cylinder assists in so shaping the electrical field in the neghborhood of the cathode that the desired degree of focusing of the cathode-ray stream upon the target shall result.

The anticathode, or target, functions at the same time as anode.

The operation is satisfactory only when the vacuum is exceedingly high, so high that the ordinary tube would carry no current even on 100,000 volts.

§ 3. THEORY OF OPERATION.

As will be seen from the characteristics of the tube, in § 5, it gives, in operation, no evidence of positive ions. This makes the theory of its operation exceedingly simple.

The discharge appears to be purely thermionic in character.

The rate of emission of electrons from the filament appears to be in accord with Richardson's Law, which says that the maximum thermionic current, which can be drawn from a hot filament is

$$i = a\sqrt{T}e^{-\frac{b}{T}}$$

where T is the absolute temperature, e is the base of the natural system of logarithms, and a and b are constants.

In the particular tube described in detail in this paper, over the range of temperatures and voltages included in the data of Table I., this simple law accounts perfectly for the conductivity of the tube. With still higher temperatures, however, the discharge currents would be found to increase at a much slower rate than that required by the above law. And the same applies, even in the temperature range of Table I., to a different tube design in which the distance between cathode and anode is greater. In these cases the failure to follow Richardson's Law at the higher temperatures has been accounted for by Dr. Langmuir[1] by the spacial density of negative electricity in the neighborhood of the cathode.

[1] L. c.

§ 4. Detailed Description of Tube No. 147.

This description relates to tube No. 147, which was used in getting the data for the following tables. Fig. 1 shows a complete assembly, while

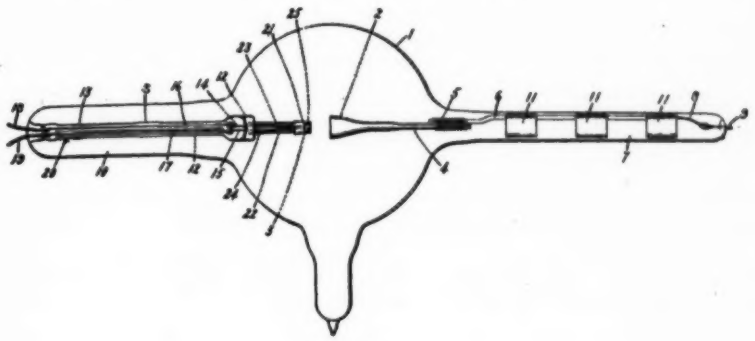


Fig. 1.

Fig. 2 shows an enlarged detail of the cathode and of the front end of the target.

The Cathode.

In the diagrams, 25 is a tungsten filament in the shape of a flat, closely wound spiral. It consists of a wire 0.216 mm. in diameter and 33.4 mm. long with $5\frac{1}{2}$ convolutions, the outermost of which has a diameter of 3.5 mm. It is electrically welded to the ends of two heavy molybdenum wires 14 and 15, to the other extremities of which are welded the two copper wires 16 and 17. These in turn are welded to the platinum wires 18 and 19. The molybdenum wires are sealed directly into a piece of special glass, 12, which has essentially the same temperature coefficient of expansion as molybdenum. This first seal is simply to insure a rigid support for the hot filament, the outer seal being the one relied upon for vacuum tightness. The outer end, 13, of the support tube is of German glass like the bulb itself, and it is therefore necessary to interpose at *S* a series of intermediate glasses to take care of the difference in expansion coefficients between 12 and 13. The small glass tube, 20, prevents short-circuiting of the copper wires, 16 and 17.

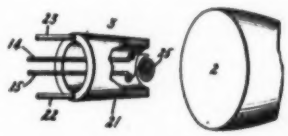


Fig. 2.

The filament is heated by current from a small storage battery which is, electrically, well insulated from the ground.

In the circuit are placed an ammeter and an adjustable rheostat and, by means of the latter, the filament current can be regulated, by very

fine steps, from 3 to 5 amperes. Over this current range, the potential drop through the filament varies from 1.8 to 4.6 volts and the filament temperature from 1890 to 2540 degrees absolute.

The Focusing Device.

This consists of a cylindrical tube of molybdenum, 21. It is 6.3 mm. inside diameter and is mounted so as to be concentric with the tungsten filament, and so that its inner end projects 1.0 mm. beyond the plane of the latter. It is supported by the two stout molybdenum wires, 22 and 23, which are sealed into the end of the glass tube, 12. It is metallically connected to one of the filament leads, at 24.

Besides acting as a focusing device, it also prevents any discharge from the back of the heated portion of the cathode.

The Anticathode or Target.

The anticathode or target, 2, which also serves as anode, consists of a single piece of wrought tungsten, having at the end facing the cathode a diameter of 1.9 cm. (Its weight is about 100 gm.) By means of a molybdenum wire, 5, it is firmly bound to the molybdenum support, 6. This support is made up of a rectangular strip and, riveted to this, three split rings, 11, 11, 11, all of molybdenum. The split rings fit snugly in the glass anode arm, 7. They serve the double purpose of properly supporting the anode and of conducting heat away from the rectangular strip and so preventing too much heat flow to the seal of the lead-in-wire, 9.

The Bulb.

This is of German glass and about 18 cm. in diameter.

The Exhaust.

This is as thorough as possible.

For the earlier tubes, mercury pumps were used, with a liquid-air trap between tube and pump to eliminate mercury vapor. The whole tube, while connected to the pump, was in an oven and was heated at intervals to 470° C. Between heating operations the tube was operated with as heavy discharge currents as the condition of its vacuum would permit. For hours the tube would show the characteristics of an ordinary Röntgen tube, and in many cases a several days' application of the above treatment was required to entirely eliminate these characteristics and to realize an essentially pure electron discharge.

The exhaust time has been greatly reduced in two ways. The massive

tungsten anode is given a preliminary firing to a very high temperature in a tungsten-tube vacuum furnace.[1] The molybdenum support is also fired, to a somewhat lower temperature, in the same manner. In the second place, a Gaede molecular pump has been substituted for the mercury pumps and, at the same time, a very large and short connection has been adopted between tube and pump.

In the later stages of the exhaust a very heavy discharge current is maintained continuously on the tube for perhaps an hour, the temperature of the bulb being kept from rising too high by the use of a fan.

The pressure in the finished tube is very low, certainly not more than a few hundredths of a micron and probably much less than this.

Connections and Method of Operating.

The tube was connected as shown in the diagram, Fig. 3, in which, T is the tube; B is a small storage battery; A is an ammeter; R is an adjustable rheostat which can be controlled from behind the lead screen

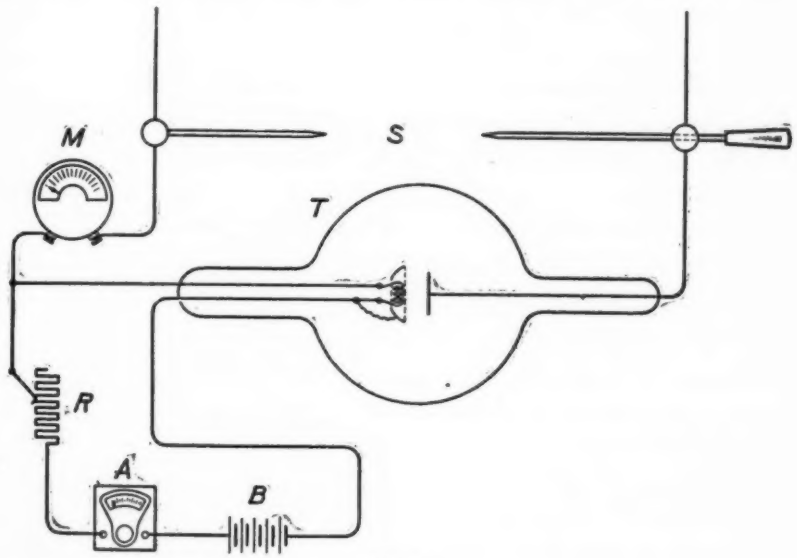


Fig. 3.

which shields the operator from the Röntgen rays; S is an adjustable spark gap with pointed electrodes, which can also be operated from behind

[1] A description of this furnace will be published in the near future. The heating element consists of a tungsten tube 2.5 cm. inside diameter and 30 cm. long. This is fastened in an upright position and, by means of suitable terminals, is connected to a 100 K.W. transformer. The heating element is placed in a water-cooled metal cylinder and the space within connected to a pump which maintains, with the furnace at its highest temperature, a vacuum of a few microns.

the lead screen; and M is a milliampere-meter which can be read from behind the screen.

As the high potential is connected to the battery circuit it is necessary that the latter shall be thoroughly insulated from the ground.

As a high potential source, a 10 K.W. Snook machine, made by the Röntgen Apparatus Co., was used. This consists of a rotary converter driven from the direct current end and delivering alternating current at 150 volts and 60 cycles per second to a closed magnetic circuit step-up transformer with oil insulation. From the secondary of this transformer the high voltage current is passed through a mechanical rectifying switch (which is direct-connected to the shaft of the rotary) and the milliampere-meter, M, to the tube. The output of the transformer is controlled by a variable resistance in the primary.

Throughout these experiments a fan was kept blowing on the tube. Without this fan, the gas pressures in the tube would be slightly higher, and the discharge currents would be in consequence slightly lower.

§ 5. CHARACTERISTICS.

A. No Discharge Current unless Filament is Heated.

Unless the filament is heated, the tube shows no conductivity in either direction, even with voltages as high as 100,000.

B. Tube Allows Current to Pass in only One Direction.

The tube suppresses any current in the direction which does not make the hot filament cathode. It is therefore capable of rectifying its own current when supplied from an alternating source.

In the case of a focusing tube, however, the use of alternating current will very considerably lower the maximum allowable energy input. For as soon as the target becomes heated at the focal spot to a temperature approximating that of the filament, the tube will cease to completely rectify and, as the temperature of the focal spot rises, will allow more and more current to pass in the wrong direction. This, to be sure, will not cause either a harmful vacuum change or a metallic deposit on the bulb, as it would in the case of the ordinary tube, but it will give rise to needless heating of the bulb where it is bombarded by the cathode rays from the target, and to disturbing Röntgen rays emanating from the glass at this point. In the case of a tube which does not focus, but in which the cathode rays bombard the entire surface of the anode, the allowable energy input which the tube will completely rectify can be increased to any desired amount by simply increasing the surface of the anode.

C. Discharge Current Determined Primarily by Filament Temperature.

With a given design, the amount of discharge current which can be passed through the tube is determined primarily by the temperature of the filament, and responds instantly to changes in the same in either direction.

The effect of both temperature and voltage on the discharge current, in the case of tube No. 147, illustrated in Fig. 1, may be seen by referring to Table I., which gives the data on the finished tube after it had been sealed off from the pump. The focal spot was 3 mm. in diameter.

In the table, Column I. gives the length in centimeters of the equivalent spark gap.

Column II. gives the heating current (C) in the filament, expressed in amperes.

Column III. gives the filament temperature (T), expressed in degrees absolute, corresponding to the values of C in Column II. The temperature values were obtained by comparison with a previously calibrated tungsten lamp.

Column IV. gives the discharge current (i) through the tube, in milliamperes.

Column V. gives the calculated values of $(-\log i/\sqrt{T})$ to the base 10.

Column VI. gives calculated values of $(.434/T \times 10^6)$.

To obtain the data in the table, the experimental procedure was as follows: The filament current was first set at a predetermined point. The spark gap was next set, also at a predetermined point. The tube was then excited and the voltage across the tube terminals adjusted (by varying the resistance in the primary circuit of the transformer) until sparks were occasionally jumping across the parallel spark gap. The discharge current value was then read off from the milliammeter.

The filament current was then raised to a second predetermined value. This increased the discharge current and lowered the potential across the tube terminals. The latter was then raised to its original value and and the new discharge current reading was obtained.

In this way the discharge current value, for a given voltage, was brought up by steps to the point where the tube finally began to show signs of instability. The temperature-current series was then repeated with a different voltage.

The values of discharge current and temperature, for each voltage, are plotted in Fig. 4. The different curves are seen to lie very close together, showing that over the range of voltages employed, the magnitude of the discharge current is practically independent of voltage.

This shows that the current in these experiments was always the saturation value.[1]

According to Richardson, the relation between the saturation current flowing from a hot filament and the absolute temperature of the filament, is expressed by the equation $i = a\sqrt{T}e^{-\frac{b}{T}}$, in which i is the current, T is the temperature, and a and b are constants of which the first has

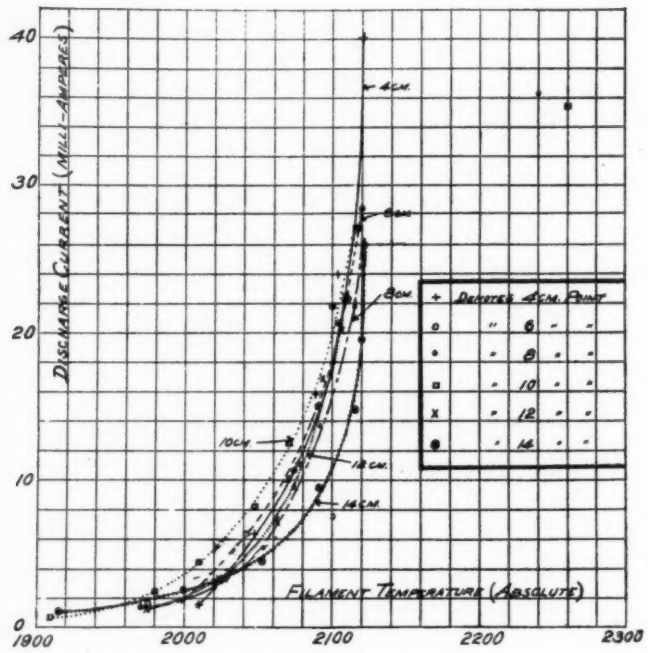


Fig. 4.

to do with the concentration of electrons within the hot body, and the second represents the amount of work required to get the electron through the surface of the metal. e is the base of the Naperian system of logarithms.

Richardson[2] applies this equation to his data by first taking the logarithm, to the base 10, of both sides of the equation, which gives

$$\log i = \log a + \tfrac{1}{2}\log T - \frac{b}{T}(.434)$$

or

$$-\log\frac{i}{\sqrt{T}} = b\,\frac{.434}{T} - \log a,$$

which is the equation of a straight line.

[1] The two points to the extreme right of the curves correspond to an unstablec ondition of the tube. The instability disappears instantly upon lowering the filament temperature.

[2] O. W. Richardson, Proc. Camb. Phil. Soc., *11*, p. 293 (1901).

TABLE I.

I. Equivalent Spark Gap (Cm.).	II. Filament Current C (Amps.).	III. Filament Temp. T (Degs. Abs.).	IV. Discharge Current i (Milliamps,).	V. $-\text{Log}\frac{i}{\sqrt{T}}$	VI. $\frac{.434}{T}\times 10^6$
4	3.40	2010	1.7	1.4212	216.1
	3.45	2028	3.5	1.1094	214.1
	3.51	2049	6.4	.4985	212.0
	3.60	2077	11.3	.6056	209.1
	3.66	2088	15.8	.4611	208.0
	3.67	2104	24.0	.2813	206.4
	3.71	2116	27.0	.2313	205.3
	3.73	2121	40.0	.0611	204.8
6	3.29	1976	1.6	1.4438	219.8
	3.43	2020	3.3	1.1341	215.0
	3.52	2053	6.5	.8433	211.5
	3.59	2074	10.6	.6331	209.4
	3.64	2090	15.3	.4753	207.8
	3.70	2110	22.3	.3138	205.8
	3.72	2120	28.3	.2113	204.9
8	3.27	1970	1.6	1.4431	220.4
	3.43	2020	2.9	1.1902	215.0
	3.53	2055	5.7	.9005	211.3
	3.59	2074	9.7	.6716	209.4
	3.64	2090	13.8	.5201	207.8
	3.71	2116	21.8	.3242	205.3
	3.73	2121	26.2	.2449	204.8
	4.07	2240	36.2	.1164	193.9
10	3.09	1909	0.6	1.8411	227.5
	3.31	1980	2.5	1.2504	219.4
	3.40	2010	4.4	1.0081	216.1
	3.50	2046	8.2	.7416	212.3
	3.57	2070	12.6	.5576	209.8
	3.67	2104	20.7	.3455	206.4
	3.65	2096	21.8	.3222	207.2
	3.71	2116	27.0	.2313	205.2
	4.13	2259	35.4	.1279	192.3
12	3.28	1973	1.7	1.4171	220.2
	3.44	2023	3.4	1.1215	214.7
	3.55	2061	7.3	.7937	210.7
	3.57	2070	10.1	.6537	209.8
	3.65	2093	16.9	.4325	207.5
	3.68	2107	22.4	.3116	206.1
	3.68	2107	20.1	.3586	206.1
14	3.11	1917	1.0	1.6413	226.6
	3.36	1998	2.5	1.2624	217.4
	3.52	2053	4.5	1.0030	211.5
	3.64	2090	8.6	.7255	207.8
	3.71	2116	14.7	.4954	205.3
	3.72	2120	19.6	.3708	204.9
	3.73	2121	26.0	.2482	204.8

If then the values of Columns IV. and V. are plotted, they should lie along straight lines, provided conduction in the tube, between the voltage limits used, follows Richardson's Law.

Reference to the plots, Figs. 5 and 6, will show that the points are closely represented by straight lines. By reading off the tangents of the angles which the lines make with the horizontal axis we get the following values of the constant b:

Voltage Corresponding to Spark Gap of	Value of b.
4 cm.	115,000
6 cm.	93,000
8 cm.	94,000
10 cm.	71,000
12 cm.	76,000
14 cm.	60,000
Average	85,000

These values of b are interesting in that they all fall within the range of the values which are just being published by Dr. Langmuir. His

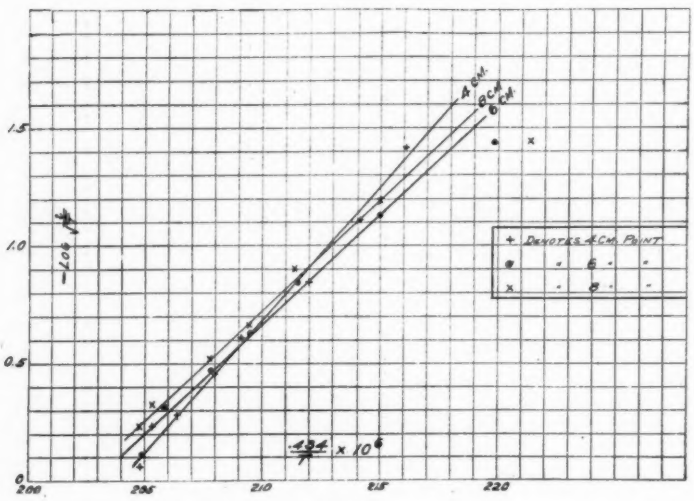


Fig. 5.

values were obtained from an apparatus in which the electrodes were fine tungsten filaments having a total mass perhaps 1/100,000 of that of the target in the above tube. His results show the enormous effect of gas on the value of b, and the conclusion can, therefore, be drawn, that very large tungsten masses can be used in a tube without, to any appreciable extent, impairing the vacuum, even though these masses may be heated close to their melting point.

If the temperature of the filament is low, only a small number of electrons escape from it and, consequently, only a small discharge current (the saturation current) can be sent through the tube. Increasing the impressed voltage above that needed for this current value causes no further increase in current. It simply increases the velocity of the cathode rays and hence the penetrating power of the Röntgen rays.

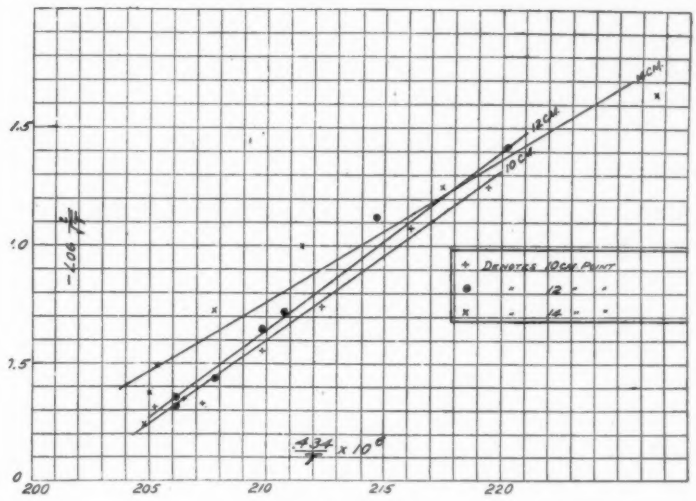


Fig. 6.

At higher filament temperatures there is a current-limiting factor, other than the number of electrons emitted by the hot filament, which plays a dominating part. This factor is the spacial density of negative electricity in front of the cathode, which amounts, in effect, to a back electromotive force. This factor would play a very important rôle at lower voltages; but in the case of the Röntgen ray tube the voltages involved are so high that, in case a suitable design is used, its influence can be entirely avoided, as is shown by the data of Table I.

D. Penetrating Power of Röntgen Rays Determined by Voltage across Tube Terminals.

The penetrating power of the Röntgen rays coming from the tube increases with the potential difference between tube terminals.

With the tube excited from a variable potential source, such as the transformer, it did not seem safe to predict that, with the same equivalent spark gap, the rays would show, photographically, the same penetrating power as those from a standard tube. But upon making the experiment, using a Benoist penetrometer,[1] it was found that they did.

[1] M. L. Benoist, C. R., *134*, 225 (1902).

The experiment was interesting from another point of view in that it showed how readily the new tube could be adapted to a given set of conditions.

An exposure was made first with a standard tube of the ordinary type, and the discharge current and equivalent spark gap were noted. A tube of the new type was then set up in place of the standard. It was but the work of a moment to adjust the new tube to the point where it showed the same discharge current and equivalent spark gap as the standard tube. The radiographs of the penetrometer, made with the two tubes, showed the same penetration number.

E. Capable of Continuous Operation without Change of Characteristics.

That the tube may be operated continuously without showing an appreciable change in characteristics is shown by the following experiment on Tube No. 147, illustrated in Fig. 1.

The filament current was set at 4.1 amperes. This gave a discharge current of 25 milliamperes. The impressed voltage was then set at a point where the tube showed a 7 cm. equivalent spark gap.

The tube was then run continuously, with no adjustment of any kind, for 50 minutes. The readings of discharge current and equivalent spark gap, taken every two minutes, are given in Table II.

F. Sharpness of Focus.

Sharpness of focus is determined mainly by the design of the tube. If the filament temperature is such that, with the voltage employed, the discharge current does not represent the saturation value, the size of the focal spot will vary with the impressed voltage. But in the tube shown in Fig. 1, over the range of voltages corresponding to an equivalent spark gap ranging from 4 to 14 cm., the focal spot does not vary appreciably in size.

The tube may be made to focus more sharply by increasing the distance between the filament and the front (end facing the target) of the molybdenum tube. This change in design will also affect the temperature-current characteristics of the tube in the direction that a higher filament temperature will be needed for a given discharge current value.

Similarly it may be made to focus less sharply by decreasing the distance between the filament and the front of the focusing device.

All of the observations made are consistent with the idea that focusing is determined by the shape of the equipotential surfaces which may be drawn in the space between cathode and anode, and that the surfaces close to the cathode have the strongly preponderating influence.

TABLE II.

Time.	Discharge Current (Milliamps.).	Equivalent Spark Gap (Cm.).
11:48 A.M.	25	7.0
:50	25	7.0
:52	25	6.9
:54	25	6.5
:56	25	6.5
12:00 P.M.	25	6.7
:02	25	6.9
:04	25	6.5
:06	24	6.4
:08	24	6.5
:10	24	6.5
:12	23	6.6
:14	25	7.0
:16	25	6.8
:18	24	6.8
:20	25	6.9
:23½	23	6.7
:26	23	6.9
:28	25	6.9
:30	25	6.9
:32	25	7.0
:34	24	6.9
:36	25	7.0
:38	24	7.1

Near the cathode, the velocity of the electrons is relatively small, and the direction of their motion will therefore conform closely to the direction of the strong electric force. Near the anode, on the other hand, the velocity of the electrons is so high that the same force acting over the same length of path will produce but little deflection.

G. Fixity of Position of Focal Spot.

The focal spot on the anode does not wander, but remains perfectly fixed in position. This is in sharp contrast to the ordinary Röntgen tube in which the focal spot does move about, and often so rapidly as to be noticeable even during the shortest radiographic exposures.[1] The effect of movement of the focal spot is, of course, to cause in the radiograph or on the screen, a blurring of all lines except those parallel to the direction of motion. In the earlier stages of exhaustion, while the new tube is being operated with a relatively poor vacuum, the focal spot may dance about, but as the electrodes and the glass become freer from gas the

[1] See Dr. Pfähler, Fortschritte auf dem Gebiete der Röntgenstrahlen, *18*, pp. 340–343 (1911–1912).

motility of the focal spot decreases and finally disappears completely. Its disappearance goes hand in hand with the disappearance of fluorescence of the glass, discussed in section *J*. Movement of the focal spot appears to be due to the action of positive ions in disturbing the distribution of static charge on the glass walls of the tube.

H. Tube not Sensitive to Considerable Changes in Gas Pressure.

The gas pressure within the tube is so low that it can increase several-fold, and apparently decrease without limit, without appreciably affecting the other characteristics.

The slight effect of pressure change may be seen from the following experiment:

While one of the tubes was being continuously operated on the pump, the pressure, as indicated by a McLeod gage, decreased from 0.113 to 0.035 micron.[1] The discharge current passing through the tube remained constant at 3.1 milliamperes, while the parallel spark gap backed up by the tube changed only from 7.9 to 8.6 cm. A corresponding pressure change in the case of an ordinary Röntgen tube would bring about an enormous change in current and voltage.

I. Capable of Continuous Operation with High Energy Input.

Owing to the fact that the tungsten target can run at such a high temperature, large amounts of energy can be continuously radiated.

J. No Fluorescence of Glass.

When operating properly the tube shows no fluorescence of the glass at any point. Corresponding to this, there is an absence of the usual strong local heating of the anterior hemisphere. The absence of fluorescence and of local heating seem to point to the fact that there is no bombardment of the glass by secondary cathode rays sent out from the target. This is in striking contradistinction to what takes place in an ordinary Röntgen tube, where, in the case of a platinum target, it has been found that there are about three-fourths as many electrons leaving the target, and going to the glass, as secondary cathode rays, as there are bombarding it, in the form of primary cathode rays. This elimination of secondary cathode ray bombardment prevents the production of a large part of the useless and disturbing Röntgen rays which emanate from the glass in the case of the ordinary tube.

The absence of bombardment of the glass is of interest both theoreti-

[1] In the light of later experiments it seems doubtful whether a further pressure decrease, no matter how great, would have appreciably affected the tube characteristics.

cally and practically. Other explanations of the lack of fluorescence suggested themselves at first. A plausible hypothesis was that bombardment took place, but that the surface of the glass was much freer from gas than it is in the ordinary tube and that this accounted for the lack of fluorescence. But the fact that fluorescence appears so suddenly when a trace of gas is evolved, coupled with the fact that such fluorescence may appear in streaks and that these may rapidly change their location, seems to disprove the hypothesis. It also seemed possible at first that the fluorescence might be there, but that it could not be seen because of the strong light emission from both filament and target. But this hypothesis is disproved by the fact that with filament and target at their highest temperatures, fluorescence becomes suddenly strongly visible whenever gas is liberated.

The simple explanation appears to be based upon the fact that the large number of positive ions present in an ordinary Röntgen tube is here lacking. The inner surface of the glass becomes strongly negatively charged, when the tube is first operated, and, not being able to attract an appreciable number of positive ions, remains so. The presence of this negative charge upon the glass prevents further electrons, either in the shape of primary or secondary cathode rays, from going there.

K. Identity of Starting and Running Voltage.

The starting, or break-down, voltage of the tube is the same as the running voltage. This is very different from the state of affairs in the ordinary tube in which the break-down voltage is much higher than the running voltage.[1] The difference is to be explained as follows: In the ordinary tube the number of ions present when the circuit is closed is exceedingly small, being only that due to natural ionization causes, such as radioactive matter in the surroundings. After the discharge circuit is closed, the number of ions increases, by collision, very rapidly, and the voltage across the tube terminals falls in consequence. In the case of the new tube, on the other hand, the full supply of electrons is there the instant the discharge circuit is closed, and even before this, and the available number is not changed by the discharge current.

L. Permits of Realization of Homogeneous Bundle of Primary Röntgen Rays.

The tube must permit of the realization of a strong homogeneous bundle of primary Röntgen rays of any desired penetrating power. For this

[1] See Dessauer, l. c.

purpose it should clearly be excited from a source of constant potential. The result should be attained even though the discharge is intermittent.[1]

M. No Heating of Cathode by Discharge Current and no Evidence of Cathodic Disintegration.

An earlier experiment showed that when a tube is made up with two similar concave tungsten electrodes, symmetrically located in the tube, and operated on direct current at an ordinary Röntgen tube vacuum, the heating effect at the cathode is as strong as that at the anode. Furthermore, the heat evolution at the cathode is as strongly localized as it is at the anode. In fact, it is impossible, when the tube is operating, to tell, by looking at it, which of the white hot electrodes is functioning as anode and which as cathode. There is a very rapid blackening of the bulb in such a tube, the material of the deposit coming evidently from the cathode, which shows a deep and sharply defined cavity at the point of local heating. The simple explanation seems to be that the cathode is bombarded by positive ions and that the emission of the electrons which constitute the cathode ray stream is due to this bombardment. So, also, the heating effect and the cathodic disintegration.

At the higher vacuum and with the relatively gas-free electrodes of the new tube there is no evidence of any bombardment of the cathode. In the earlier stages of gas removal, when a discharge can be made to pass through the tube without the heating current in the filament, the latter is seen to be strongly locally heated by the discharge current, as from bombardment by positive ions. But when the exhaustion has been completed and the tube is operated with the cathode hot, a voltmeter and ammeter in the filament circuit show no change even when a very heavy discharge is sent through the tube. Positive ion bombardment, if it existed to an appreciable extent, would raise the temperature and, hence, the resistance of the tungsten filament and would therefore be indicated by the instruments. If it were very local and considerable, it would be further indicated by a melting through of the filament at the point in question. The resistance change and local disintegration of the filament have been observed in only those cases where the vacuum, as shown by other effects, such as fluorescence of the glass, has been poor.

Disintegration of the cathode would also manifest itself in blackening of the bulb. Even after running for several hours, the deposit on the bulb is very slight, and what there is may well be entirely accounted for by vaporization of tungsten at the focal spot on the target.

[1] For fluoroscopic work with the ordinary tube, it seems preferable to use an interrupted discharge so as to reduce heating of the tube and danger to patient and operator. The phosphorescence of the fluoroscopic screen makes possible frequent interruptions without appreciable loss of light.

N. The Target the Factor Limiting Allowable Energy Input.

There is one limitation with the new tube. With a sharp focusing tube and above a certain energy input the tube resistance is unstable, dropping suddenly to perhaps a small fraction of its original value, returning instantly to the old value however upon stopping the discharge or upon lowering it to the limiting value. The cause of this phenomenon appears to be as follows:

With a very high energy input and sharp focusing, the surface of the target melts at the focal spot and volatilizes. Owing to the fact that this tungsten vapor is produced at the focal spot, all of the primary cathode rays pass through it and, by collision, ionize it. This of course decreases the tube resistance. The larger the focal spot the greater is the limiting current. The design of the target also has a great deal to do with the limiting current value, as the face of a thin target is vaporized with a much lower energy input than a relatively thick one. For very short excitation of the tube, the limiting energy input is somewhat larger than for longer periods; but an input which can be carried for a few seconds can be carried indefinitely.

The effect of substituting any other single refractory metal for the tungsten of the target will be to lower the maximum allowable energy input. For the essential properties of a target material are: high density, high melting point, high heat conductivity, and low vapor pressure. Tungsten has a higher melting point and lower vapor pressure than any other metal. Its nearest competitor in point of refractoriness, tantalum, has only about one third of the heat conductivity. Molybdenum and iridium have vapor pressures altogether too high to entitle them to consideration, even if their melting points made them otherwise competitors. Osmium has only about one half of the heat conductivity of tungsten.

The ordinary copper-backed tungsten target would be very difficult to exhaust sufficiently. Otherwise its use might be desirable for certain classes of work, as it would raise the maximum allowable instantaneous energy input.

§ 6. Danger Connected with Use of Tube.

There has been in the old tube a certain element of safety in that it could not be run continuously with a very heavy energy input. The new tube, even when focusing sharply, can be operated, for example, on a 7 cm. parallel spark gap with currents as high as 25 milliamperes for hours at a time, and without the slightest attention.

For most purposes, other than diagnostic or radiographic work, there is no advantage in having the tube focus. In case it does not, the above-

mentioned energy input limitation falls away and the tube can apparently be designed for any energy input whatsoever. This will permit, in this field, of the use of much greater Röntgen ray intensities than have heretofore been realized.

In the light of the above, it will be seen that the precautions which have been shown by years of experience to be sufficient for work with the old tube are not necessarily sufficient for the user of the new one.

§ 7. SUMMARY.

In the foregoing, a new and powerful Röntgen ray tube has been described. It differs in principle from the ordinary type in that the discharge current is purely thermionic in character. Both the tube and the electrodes are as thoroughly freed from gas as possible, and all of the characteristics seem to indicate that positive ions play no appreciable rôle.

The tube allows current to pass in only one direction and can therefore be operated from either direct or alternating current.

The intensity and the penetrating power of the Röntgen rays produced are both under the complete control of the operator, and each can be instantly increased or decreased independently of the other.

The tube can be operated continuously for hours, with either high or low discharge currents, without showing an appreciable change in either the intensity or the penetrating power of the resulting radiations.

The tube in operation shows no fluorescence of the glass and no local heating of the anterior hemisphere.

The starting and running voltages are the same.

The tube permits of the realization of intense homogeneous primary Röntgen rays of any desired penetrating power.

An article bearing especially upon the application of the new tube to radiographic and diagnostic and to therapeutic purposes will appear shortly in one of the Röntgen ray journals.

It is a pleasure to me, in closing, to express my appreciation of the services of Mr. Leonard Dempster, who has assisted me throughout this work.

RESEARCH LABORATORY OF THE GENERAL ELECTRIC CO.,
SCHENECTADY, N. Y.

THE CHANGE IN THE ELASTICITY OF A COPPER WIRE WITH CURRENT AND EXTERNAL HEATING.

BY H. L. DODGE.

THE present investigation consists of determinations of Young's modulus of a specimen of copper wire at various temperatures between 20° C. and 150° C. with the object of ascertaining whether or not heating by an electric current has any effect other than that caused by the accompanying increase of temperature, and also to learn certain facts regarding the temperature effect itself, concerning which there seems to be considerable doubt.

PREVIOUS RESULTS UPON THE EFFECT OF CURRENT HEATING.

Wertheim[1] reported a decrease in Young's modulus caused by current and believed this decrease to be independent of any temperature effect, a conclusion not sufficiently justified as he assumed the heating effect of the current negligible. Edlund[2] made allowance for the temperature effect, and concluded that current, except for the accompanying temperature change, does not affect Young's modulus. Streintz[3] made observations of the torsion modulus at room temperature and at 55.5° C. The following figures represent the percentage change of elasticity caused by the current, correction being made for the temperature effect: Brass (*a*), − 5.9; (*b*), + 12.8; copper, 0.0; silver, + 3.9; iron, + 3.1; steel, − 12.2. Mebius[4] found the effect due to current in the case of steel, iron, brass, and silver rods to be extremely small. Miss Noyes[5] studied steel, silver, and copper wires and found that the current heating caused a uniform decrease in Young's modulus which could be entirely accounted for as a temperature effect. Walker[6] employed the same experimental methods as Miss Noyes, but found very irregular changes with steel, soft iron, platinum, and copper, which could not be accounted for by temperature and which differed greatly with increasing and decreasing

[1] Ann. de Chim. et de Phys., 12, 610, 1844.
[2] Annal. d. Phys., 129, 15, 1866; 131, 337, 1867.
[3] Annal. d. Phys., 150, 368, 1873.
[4] Oefvers. af k. Vet. Akad. Forhandl., 681, 1887; Beibl. 12, 678.
[5] PHYS. REV., 2, 279, 1895; 3, 433, 1896.
[6] Proc. Roy. Soc. Edin., 27, 343, 1907.

current. A survey of previous work leaves a serious doubt as to the effect of current heating, and this doubt a critical study serves to increase.

PREVIOUS RESULTS UPON THE CHANGE OF YOUNG'S MODULUS WITH TEMPERATURE.

The investigations that have been carried on to determine the change of Young's modulus with temperature are so extensive that the results with copper only can be considered. These are however representative of the results for other metals. Shakespeare[1] has found a decrease of Young's modulus for copper of 3.6 per cent. on heating from 13° C. to 100° C. Miss Noyes[2] made observations at various temperatures up to 150° C. and reports a uniform decrease of the modulus of 0.13 per cent. and 0.07 per cent. per degree for two samples of wire. Gray, Blyth, and Dunlop[3] also were able to make observations at intermediate temperatures up to 100° C. They also report a uniform decrease, which for two samples was 0.015 per cent. and 0.04 per cent. per degree respectively. On the other hand Slotte's[4] observations at intervals over a range of 10° C. to 70° C. upon two samples of copper wire showed a decrease of Young's modulus with increase of temperature which was not uniform but became less rapid with one sample and more rapid with the other as the temperature increased. An increasing rate of change is also indicated by the results of Wertheim[5] at 15° C., 100° C., and at 200° C., the change being much greater for the upper interval. In this connection the work of Pisati,[6] Kohlrausch and Loomis,[7] and of Slotte[8] upon the torsion modulus is of interest. They found the rate of decrease of the modulus greater as the temperature was raised. This is suggestive as it is highly probable that the general nature of the elastic changes is similar for the two moduli. These results leave no doubt that increase of temperature causes a decrease of Young's modulus, but there is no conclusive evidence as to the exact nature of the decrease.

SCOPE OF WORK.

In view of the facts which have been cited it was decided to attempt an investigation of the effect of current upon Young's modulus, accompanied by a parallel investigation of the temperature change produced by an

[1] Phil. Mag., 47, 539, 1899.
[2] Loc. cit.
[3] Proc. Roy. Soc., 67, 180, 1900.
[4] Acta Soc. Scien. Fennicæ, Vol. 26, 1899.
[5] Loc. cit.
[6] Nuovo Cimento, 4, 152, 1878; 5, 34, 135, 1879.
[7] Annal. d. Phys., 141, 481, 1871.
[8] Acta Soc. Scien. Fennicæ, Vol. 35, 1908.

external source of heat. Examination of the previous work led me to believe that the desideratum was not a hastily made series of observations upon a number of metals but rather thorough and extended observations upon a single metal. Consequently this report is confined to results with copper although work is under way with other metals. A review of the literature made clear that the causes of inaccurate results in the past have been chiefly a lack of mechanical perfection in the apparatus and insufficient attention to the distribution of temperature. In none of the work upon the effect of current has there been any knowledge of the differences in temperature along the wire or any effective attempt made to secure a uniform distribution. The apparent crudity of the apparatus that is here described is the result of an attempt to keep every part of the apparatus as simple as possible and to refrain from unwarranted refinements. Each source of error has been considered in relation to the others and the effectiveness of the apparatus is best judged from the consistency of the results that have been obtained.

Description of the Apparatus.

In order to prevent convection currents and consequent non-uniformity of heating necessarily accompanying vertical suspension the wire was mounted horizontally. The mechanical features of the apparatus (Fig. 1) may be considered independently of the heating box. The wire is

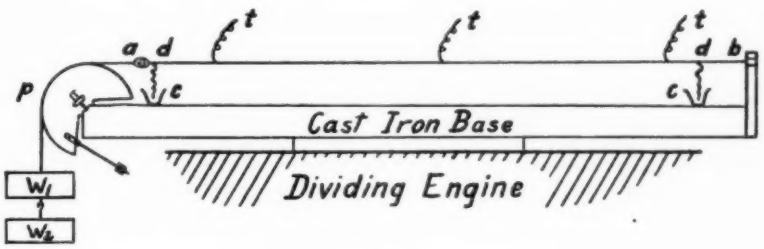


Fig. 1.

The apparatus, showing method of suspending the test specimen.

suspended between a bar (b) and a pulley (p) which are in turn supported by a heavy cast iron base, bolted to the carriage of the dividing engine. The wire is stretched by the weights W_1 and W_2. Current is led in at the points (d) through the mercury cups (c), the wire being insulated at (a) and at (b). Three copper-constantan thermo-couples (t) of No. 36 wire are for temperature measurements. The weight W_1 is kept upon the wire continually and is heavy enough to stretch the wire almost straight. The weight W_2 is added gradually and without jar by a simple

apparatus operated by a foot lever. The elongation of the wire is measured with two micrometer microscopes attached to the bed of the dividing engine. These are focused upon bright scratches on the wire, made visible by incandescent lamps.

The heating apparatus (Fig. 2), although supported by the cast-iron base, is mechanically entirely independent of the wire. It must not only furnish a means of heating the wire externally but also must retain the heat when the current is passed through the wire itself. The base (*o*), bottom piece (*s*), and back (*v*) are covered with asbestos and fastened together. The asbestos-covered front (*h*), which has two windows of mica (*m*) for observing the wire, and the glass cover (*n*) are held together by clamps easily removed. The glass tubes (*k*) are large enough to give sufficient clearance to the wire (*w*) but small enough to prevent convection or other air currents. Zigzagging back and forth across the bottom piece (*s*) is a heating wire of German silver through which a current can be

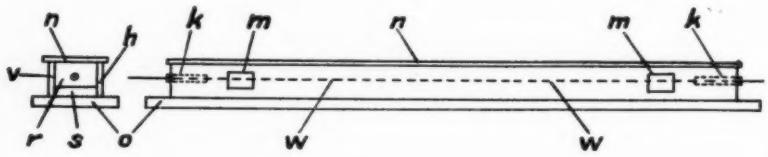


Fig. 2.

Heating box surrounding the test specimen.

sent. This heating box proved to be one of the three important features of the apparatus and its simple form in no way indicates the difficulty of securing a reasonably even temperature distribution. This fact is very suggestive in connection with the results of former investigations in which average temperature only was known, there being no information concerning the temperature distribution. The use of thermo-couples which could be slipped to different portions of the wire revealed surprising inequalities of temperature. Even after uniformity of heating had been secured with the external source it was necessary to still further alter the box before a satisfactory distribution could be obtained with internal or current heating. At the highest temperature employed the maximum variation of temperature over the portion of the wire under observation was less than 15° C.

A second feature of importance is the free suspension of the wire. The possibility of error due to contact of the wire with rigid portions of the apparatus is eliminated by permitting it to touch nothing except the thermo-couples which are of fine flexible wire. Consequently the specimen hangs freely in the form of a flat catenary. The elongation

caused by the straightening of the catenary on the application of the additional stretching weight is negligible, being about 1/100 of the smallest reading of the micrometer microscope. The third feature is also mechanical. It is the pulley which changes the direction of the applied force, which must be transmitted without gain or loss resulting from friction or change of leverage. Fig. 3 shows its construction and suggests the method of centering the axis. The pulley was tested at different posi-

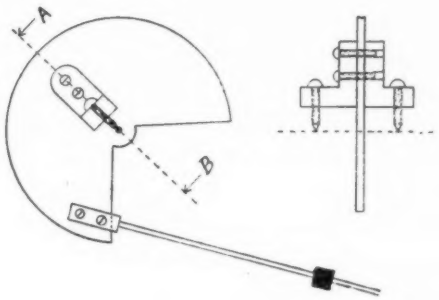


Fig. 3.

Side view of pulley and section along *A–B*.

tions at various times during the progress of the work and found to introduce no appreciable error.

Method of Determining Temperature of Specimen.

When the wire is heated by the external source it is of uniform temperature throughout its cross section and of the same temperature as the surrounding air. Under these conditions the thermo-couples which have already been mentioned are a perfectly satisfactory means of measuring its temperature. In the case of internal or current heating there is an increase of temperature toward the center, resulting in a number of effects, change of resistance, thermal conductivity, etc., each of which has its influence upon the current distribution and in turn upon the temperature distribution. The average temperature of the wire is of course a function of the surface temperature and of the current, but for evident reasons the thermo-couples do not give the surface temperature of the wire when the wire itself is the source of heat.

Measurement of temperature by change of length caused by thermal expansion has proved to be the most accurate and convenient method. Blondlot[1] has shown conclusively for several pieces of brass and one of German silver that current has no direct effect upon the dimensions of

[1] Journal de Phys., [1], 8, 122, 1879.

a metal carrying a current. This has also been shown by Righi[1] for four wires whose composition is not given. There is no reason to believe that copper should be peculiar in showing this effect. In fact our own experience and the persistency with which our results for Young's modulus at any temperature as determined by this method remain the same, no matter what may be the source of heat, is in itself proof that current has no direct effect upon the length of the wire. In using change of length as an indication of temperature account must be taken of the change caused indirectly by the effect of temperature upon Young's modulus. Thermo-couple readings and length observations were taken for all work with external heating. With internal heating length observations were made and the temperature determined by comparison with the other results. The thermo-couples were connected to a sensitive Siemens and Halske galvanometer by a three-way switch and were calibrated by direct comparison with an accurate thermometer.

With current heating the central portions of the wire tend to lengthen more than the outer portions which are at a lower temperature and it is assumed that the actual lengthening so averages this effect as to be an indication of the average temperature. It is also worthy of notice that the contribution to Young's modulus will be different for the different portions, the value observed being an average of the moduli of the various circular layers making up the cross section of the wire. There is of course a similar averaging of temperature and modulus along the length of the wire.

NATURE OF THE TESTS.

Three sections of commercial copper wire were tested, all from the same piece obtained from the Driver-Harris Wire Co., Harrison, N. J. The purity of the specimen was determined electrolytically, with results of 99.88 per cent. and 99.92 per cent. As the second was the more accurate we may take 99.91 ± .01 as the purity of the specimen. There was no trace of either silver, lead, or iron. The coefficient of linear expansion was .0000169. Specimen No. 2 was 0.81 mm. in diameter. The portion under observation was 50.7 cm. long. The other samples were of similar dimensions. A weight of 2,109 grams was kept upon the wires continually. The modulus was determined by measuring the elongation produced by an additional weight of 2,252 grams. The elongation was observed with a microscope, the micrometer head of which can be read to 1/50 revolution, corresponding to .00093 mm. stretch. At room temperature the stretch amounted to about .02 mm.

[1] Nuovo Cimento, [3], 7, 116, 1880.

Currents as high as 15 amperes were used. The accuracy of the work is of a high degree. The error in the determination of Young's modulus is about 1 per cent. A greater accuracy may prove desirable if small peculiar effects appear with other metals, but the present apparatus is sufficiently accurate to determine the general nature of the changes in the modulus.

Each determination of Young's modulus as represented by a point on the curves or a value in the tables is the result of ten or more separate measurements taken so as to eliminate any error caused by a slight drift in temperature. Generally a half hour or more was required for the temperature to reach a sufficiently steady state. After the preliminary work the greater part of the observations consisted of series of determinations with increasing or decreasing temperature over a range of 20° C. to 150° C.

Preliminary Tests.

The possible ways in which current may affect elasticity are so numerous that a determination of Young's modulus at a given temperature is of no value unless interpreted in connection with the whole thermal history of the wire. Since the essential part of this investigation is the comparison of observations taken under as nearly similar thermal conditions as possible, except for the difference in time and in the source of heat, an elimination as far as possible of any other than pure temperature effects is desirable. If this is impossible a thorough understanding of the nature of the other effects is essential. In order to eliminate the well-known permanent changes accompanying extreme temperatures the treatment of the wire after its first heating and stretching was confined to a temperature range of 20° C. to 150° C. In order to find out how consistent was its behavior within this range and under the various conditions of treatment a great deal of preliminary work was necessary. This showed that there are no sudden changes in the elastic state of the wire, that the rapidity of heating and cooling had little if any effect upon the changes in elasticity, and that the length of time the wire was held at a given temperature had no great effect. As explained later, permanent or history effects were found, but for any series of readings these changes were insignificant, the value of Young's modulus returning at the close of any day's observations to practically its original value.

That history effects could be eliminated and the elasticity of the wire made independent of treatment and a function of temperature only is illustrated in Fig. 4, Series 5. Observation 15 is almost identical with 8, and 16 and 17 are nearly the same as the first observations, although the wire had meantime been heated and cooled twice.

In order to learn whether or not at any given temperature the value of Young's modulus is dependent upon the manner of heating, the observations of Table I. were made. The shifting from one method of heating to another was done without permitting much alteration in the temperature of the wire.

TABLE I.

Showing Constancy of Young's Modulus under Different Conditions of Heating, Temperature Remaining the Same.

Method of Heating.	Variation in Length, Mm.	Variation in Stretch, Mm.
12.8 amperes, alternating current.....	.0000	.0000
12.8 amperes, direct current.....	.0065	.0009
External, direct current.....	.0059	.0009
External, alternating current.....	.0032	.0014
12.2 amperes, direct current.....	.0018	.0009

The greatest variation in length is .0065 mm. or 0.14 revolution of the micrometer head. This corresponds to a temperature variation of less than one degree Centigrade. The greatest variation in stretch is .0014 mm. This corresponds to only 0.03 revolution and is about the experimental error. These results show clearly that at this temperature, which was approximately 110° C., the stretch modulus is independent of the source of heat. These preliminary investigations and others which need not be described showed the behavior of copper to be very consistent and are the justification for the taking of more extended series of observations and the comparison of results secured at different times.

TESTS UPON SPECIMEN NO. 2.

After specimen No. 2 was placed in the apparatus it was heated to a high temperature and stretched to remove the kinks. Afterward it was never heated above 150° C. The four series of readings composing Fig. 4 were taken after the wire had been heated by both methods a total of about 50 hours and after about 500 applications of the stretching weight. If such a thing were possible as a state in which all changes in elasticity, except those caused by temperature could be eliminated, this treatment should have secured the result.

As far as possible the figures have been made self-explanatory. Certain additional information which is characteristic of all the work is given in Tables II. and III. Series 4 shows a series of observations in which the heating was entirely external. In this as well as in the other three series of Fig. 4 dotted points represent observations taken while the

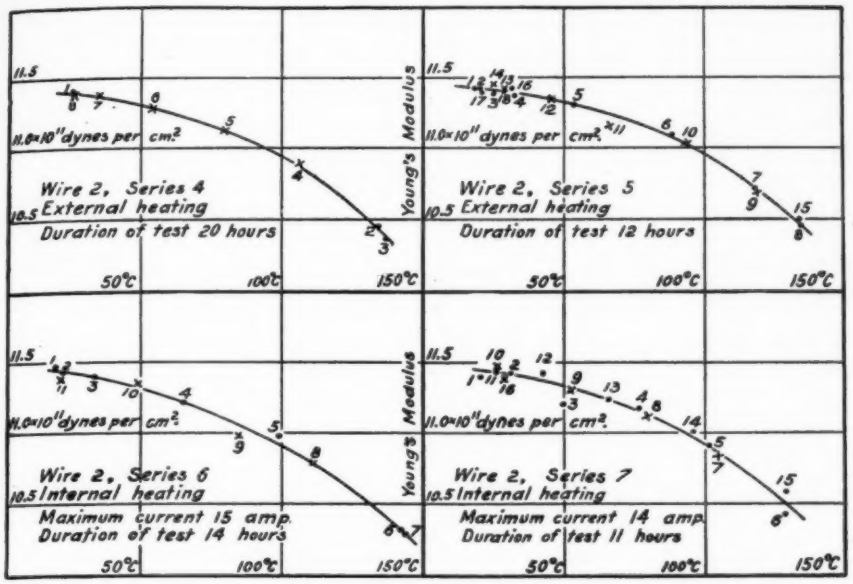


Fig. 4.

Results of tests upon specimen No. 2, showing effect of internal and external heating.

TABLE II.

Data for Series 5, Wire 2, External Heating.

Obs. No.	Time.	Temp.	Stretch (Revs. of Micr. Screw).	Young's Modulus × 10^{-11} Dynes per Cm^2.
1	9:00 A.M.	18° C.	4.08	11.46
2	9:30	20	4.08	11.46
3	10:05	25	4.10	11.42
4	10:30	33	4.11	11.40
5	11:05	54	4.13	11.33
6	11:50	88	4.205	11.11
7	1:00 P.M.	118	4.35	10.73
8	2:00	135	4.47	10.48
9	2:45	119	4.365	10.70
10	3:15	94	4.24	11.05
11	4:10	67	4.19	11.18
12	4:40	46	4.12	11.38
13		28	4.09	11.44
14	6:00	25	4.075	11.48
15	7:15	134	4.45	10.52
16	8:00	32	4.085	11.45
17	8:45	21	4.10	11.42
18	9:30	28	4.09	11.44

TABLE III.

Data for Series 7, Wire 2, Internal Heating.

Obs. No.	Time.	Temp.	Current, Amperes.	Stretch (Revs. of Micr. Screw).	Young's Modulus $\times 10^{-11}$ Dynes per Cm^2.
1	10:30 P.M.	21° C.	0.0	4.10	11.42
2	11:15 A.M.	32	3.8	4.085	11.45
3	11:50	50	7.0	4.165	11.22
4	1:05 P.M.	77	9.8	4.18	11.20
5	1:30	102	12.0	4.28	10.93
6	2:30	128	14.1	4.49	10.43
7	3:05	105	11.9	4.31	10.85
8	3:50	80	9.5	4.20	11.13
9	4:20	53	6.8	4.13	11.33
10	5:10	27	0.0	4.07	11.50
11	6:30	27	0.0	4.08	11.46
12	7:25	43	5.0	4.09	11.44
13	8:00	66	8.0	4.15	11.26
14	8:45	97	11.2	4.245	11.02
15	9:15	129	13.9	4.42	10.60
16	9:40	28	0.0	4.10	11.42

temperature was being raised by steps and the crossed points those when the temperature was being lowered. Particular attention is called to points 2 and 3, the second of which was taken after the temperature had been maintained for twelve hours. They show that the length of time the wire was kept at the high temperature had no effect upon its elasticity. The proximity of points 8 and 1 shows the elimination of history effects and permanent changes.

Two days later Series 5 was secured, which yields results identical with those of Series 4, showing that the work of one day can be repeated at a later time. Further proof of the absence of history effects is afforded by the positions of points 14, 15, 16, 17, and 18 relative to observations taken at earlier times at the same temperatures. The fact that points 5, 6, and 7 taken with increasing temperature fall on the same curve as points 9, 10, and 12 taken with decreasing temperature shows the absence of any hysteresis effects.

Series 6 was taken three days later, followed the next day by Series 7. The procedure was the same as before except for the difference in the manner of heating. In Series 4 and 5 the wire was heated externally by means of the heating wire on the bottom of the box enclosing it. In Series 6 and 7 the wire was heated by an electric current in the wire itself. The results of Series 6 and 7 show the absence of hysteresis effects and the elimination of history effects the same as with external heating. The fact that the variation of the curves forming Fig. 4 is less than would

be expected from the experimental error shows that one is justified in taking these results as an indication of temperature effect alone and is justified in comparing the results of different days with different methods of heating.

Tests upon Specimen No. 3.

A third sample of the same wire was next placed in the apparatus in order to confirm the results obtained with the former specimen, to attempt still other variations in the thermal treatment and to secures the complete elastic history of a specimen. The results are given in Figs. 5, 6, and 7. Upon these curves appear every observation that was made with the third specimen, not one having been discarded.

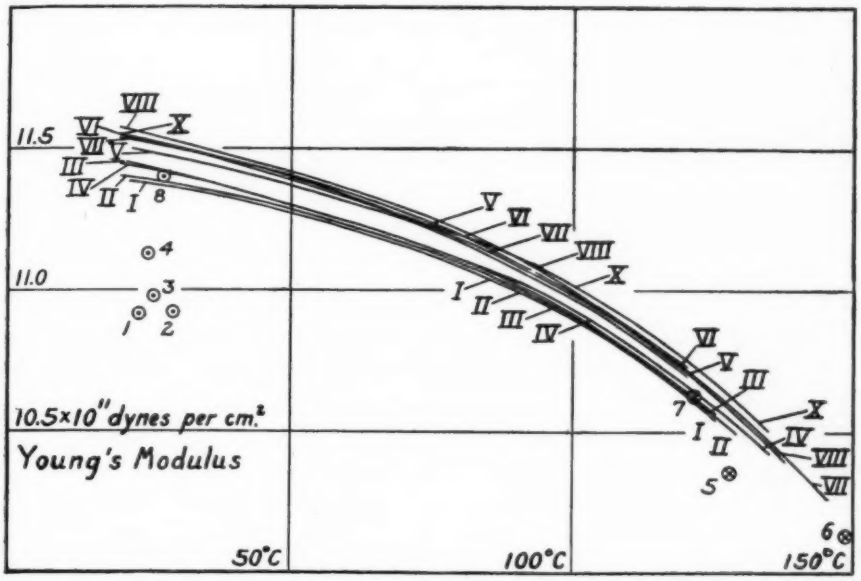


Fig. 5.

Complete elastic history of specimen No. 3. The curves are those of Figs. 6 and 7, the Roman numerals corresponding to the series numbers.

First Changes in Elasticity.—The specimen was made as free from kinks as possible and placed in the apparatus. Observation 1, Fig. 5, was at room temperature. The wire was then heated externally to about 125° C. and cooled. Observation 2 shows no change. Heating by 17 amperes current to about the same temperature brought a slight increase in the modulus as indicated by observation 3. There was very little increase in length during this treatment, as the additional weight was not applied at high temperatures.

It was anticipated that continued application of the additional weight while the wire was hot would remove any kinks in the wire, cause an increase in length and a change in the modulus. The wire was heated by 17 amperes current and the weight applied a number of times. On

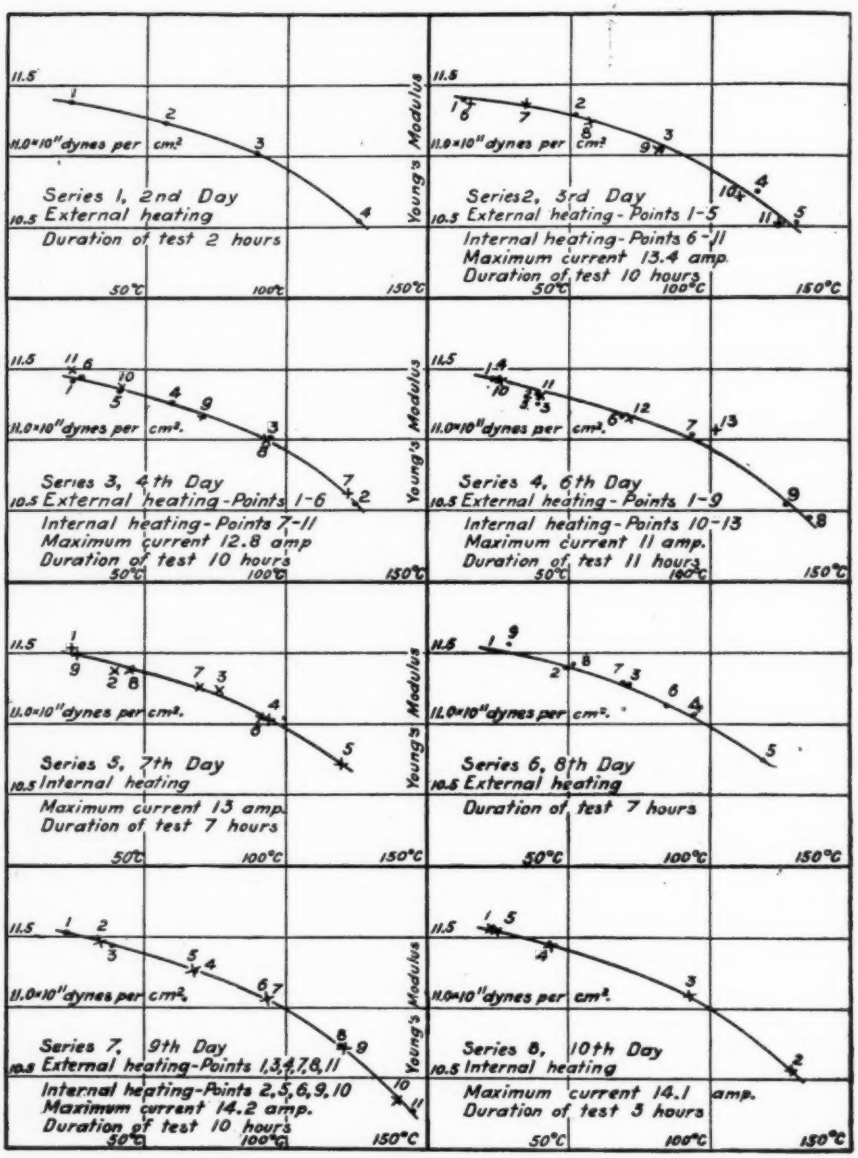

11.5
11.0×10¹¹ dynes per cm²
Young's Modulus
Series 1, 2nd Day
10.5 External heating
Duration of test 2 hours
50°C
100°C
150°C
Series2, 3rd Day
10.5 External heating - Points 1-5
Internal heating - Points 6-11
Maximum current 13.4 amp
Duration of test 10 hours
Series 3, 4th Day
10.5 External heating - Points 1-6
Internal heating - Points 7-11
Maximum current 12.8 amp
Duration of test 10 hours
Series 4, 6th Day
10.5 External heating - Points 1-9
Internal heating - Points 10-13
Maximum current 11 amp.
Duration of test 11 hours
Series 5, 7th Day
10.5 Internal heating
Maximum current 13 amp.
Duration of test 7 hours
Series 6, 8th Day
10.5 External heating
Duration of test 7 hours
Series 7, 9th Day
10.5 External heating - Points 1,3,4,7,8,11
Internal heating - Points 2,5,6,9,10
Maximum current 14.2 amp.
Duration of test 10 hours
Series 8, 10th Day
10.5 Internal heating
Maximum current 14.1 amp.
Duration of test 3 hours

Fig. 6.

Results of tests upon specimen No. 3 with different thermal treatment, showing history effect, change of Young's modulus with temperature, and absence of any effect peculiar to current heating.

cooling an increase of length of about 0.2 mm. was found and an increase of Young's modulus as indicated by observation 4. The wire was again heated to 125° C. and Young's modulus measured at this temperature, resulting in observation 5. The temperature was then increased to about 150° C. and the additional weight applied about thirty times, resulting in observation 6. Cooling to 122° C. gave observation 7, and to 28° C., observation 8. It was believed that a sufficiently steady state had been secured to justify the trial of a series of readings and a comparison of points 6, 7, and 8 with reference to later observations shows this to have been the case. It is highly probable that the increase in Young's modulus due to this particular treatment was caused as much by the mechanical stretching and straightening of the wire as by the thermal treatment, although the latter was undoubtedly essential to the securing of the steady state.

Discussion of Fig. 6.—Following the work just described came eight days of testing under a variety of conditions. Fig. 6 shows the results and has been made practically self explanatory. The order in which the observations at the different temperatures were taken and the manner of heating were varied in a number of ways in order to catch any possible changes caused by treatment. Series 1 is with external heating, increasing temperature. Series 2, first part, was taken in exactly the same manner and the results show that for external heating a sufficiently steady state had been reached so that only small permanent changes were to be anticipated. The second part of Series 2 was taken in exactly the same manner except for the change in the manner of heating, the external heating having been changed to internal by means of the current. No difference is observed. The following day a series was taken in a similar way except that the observations were made with decreasing temperature. The nature of the temperature change remains the same and a slight permanent increase appears.

In Series 4 the systematic heating and cooling over the whole temperature range was not followed, but no peculiar effects were observed. During the following night the wire lay unstretched and it is possible that this had some influence in causing the permanent increase of elasticity observed the next day. Series 5 is the result of heating and cooling with internal heating and Series 6 is for the same treatment with external heating. No hysteresis effect appears nor does there appear any difference due to method of heating.

Discussion of Series 7.—Series 7 is the most interesting single set of observations, and was taken in order to compare the two methods of heating without permitting the elapse of several hours or allowing an

appreciable change of temperature. At each temperature at which observations were taken, the change in heating was made gradually, without permitting the temperature of the wire to change. Observation 1 was at room temperature. Observation 2 was with current heating. Without permitting more than a few degrees variation in temperature the current in the wire was decreased while that in the heater was increased. Observation 3 was with external heating. The temperature was then increased and observation 4 taken. Again the method of heating was gradually changed until observation 5 was secured with internal heating at practically the same temperature. In the same way 6 and 7; 8 and 9; 10 and 11 were taken. The results show in a striking manner that the changes accompanying current heating are only temperature effects. The tests of the tenth day with internal heating gave Series 8.

In any single series of this group the permanent changes with treatment do not appear prominent. But a comparison of the eight curves, Fig. 5, reveals a gradual increase of Young's modulus from day to day. This was caused undoubtedly by the continued application of the additional weight which caused a very small gradual stretching.

Effect of the Period of Rest.—Two days after the observations of Series 8 a measurement was taken at room temperature after which the wire was undisturbed for 106 days. This last observation appears with Series 9, Fig. 7, and a comparison with point 1 shows a slight recovery of

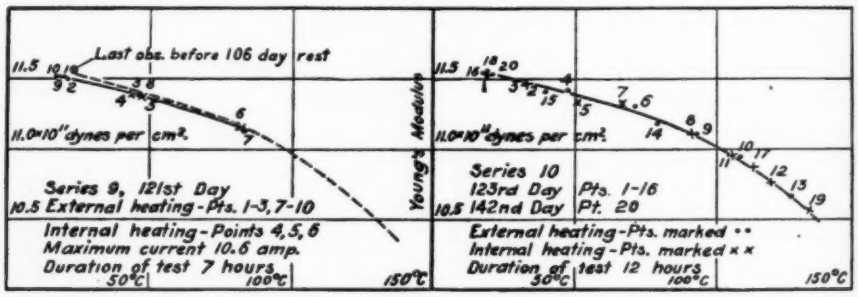


Fig. 7.

Results of tests upon specimen No. 3 after 106-day rest.

the wire during the long rest. Nine other observations were then taken with an idea of determining whether or not the modulus would remain low upon heating. This proved to be the case both for external and current heating as is clearly brought out by comparison with the dotted line which is the Series 8 curve. Two days later, as shown by Series 10, further heating and testing brought the specimen back to its former state

for low temperatures although at high temperatures greater values of Young's modulus were observed than ever before. Too much stress must not be laid upon these slight changes in the wire. The difference between Series 9 and Series 8 is small and may have its origin in a slight change in the working condition of the apparatus caused by its period of idleness. The important fact is that no great change occurred and the wire was in practically the same condition as when left. The explanation of the difference in slope in some of the curves is that the experimental error is of about the amount of the variation. The total change in Young's modulus over the entire temperature range is only 10 per cent. and the difference in stretch which this represents corresponds to less than one revolution of the micrometer head. In order to show this variation the scale to which Young's modulus is plotted has to be so large that the errors of observation become appreciable. When the magnitude of the probable error is taken into consideration the consistency of the curves taken under such a variety of conditions is remarkable.

Conclusions.

The following conclusions apply to the sample of copper wire that has been studied. I am of the opinion that other specimens of copper will yield results differing only in the magnitude of the changes, and believe that the results are very suggestive of the effects that can be expected in other metals. But work with iron wire now under way and certain results of other investigations to which reference is made later makes me feel that too great caution cannot be exercised in making general conclusions from observations upon particular samples.

From the preliminary observations and the tests upon specimens Nos. 2 and 3 we reach these conclusions:

1. A copper wire can be brought to a steady elastic state in which the stretch modulus becomes a function of temperature. In the present instance it was brought about by repeated stretching and heating and cooling over a range of temperature of 20° C. to 150° C. The preliminary tests show that the rate at which the heat was applied or at which the wire was cooled, the length of time the temperature was maintained, and the thermal route by which a given temperature was reached had no apparent effect upon the value of the modulus at any given temperature. These same facts are brought out still more convincingly by the extended work upon specimens 2 and 3, which also show that permanent changes in the modulus can be practically eliminated by a relatively small amount of heating and stretching, which if continued for a longer time renders them negligible.

2. Heating by an electric current has no effect other than that caused by the accompanying temperature. This was proved for one temperature by the results of Table I. and at a number of different temperatures by the work of Series 7, Wire 2, shown in Fig. 6, in which the heating was alternately by current and the external source.

Further proof with step by step heating is also furnished by the identical nature of the results recorded in the four curves of Fig. 4, two curves of which are for current and two for external heating. Conclusive evidence is afforded by the long series of experiments carried out upon the third specimen, in which every possible way of varying the methods of heating was attempted without detecting any difference in the results.

3. Young's modulus of a copper wire decreases with increase of temperature at an increasing rate. In the case of the specimen studied, the amount of decrease at different temperatures in terms of per cent. of the value of the modulus at 20° C. is as follows: 40° C., 0.6 per cent.; 60° C., 1.7 per cent.; 80° C., 2.9 per cent.; 100° C., 4.6 per cent.; 120° C., 7.0 per cent.; 140° C., 10.0 per cent. At 20° C. the modulus of the sample in the steady elastic state was 11.5×10^{11} dynes per cm^2.

The true nature of the temperature change was first shown by the work with specimen 2 as represented by the curves of Figs. 4 and was fully substantiated by the further work with specimen 3 which yielded identical results.

4. Heating and repeated stretching increases Young's modulus. As is shown by the results with specimen 3 there is an apparent increase of about 5 per cent. caused by the first four heatings and the accompanying stretching, which is thought to be due in part to the straightening out of the kinks. But there was a further increase of 2 per cent., which was a true history effect, although caused probably as much by the repeated stretching as by the heating.

Comparison with Results of Others.

As has already been stated previous results upon the effect of current do not agree. A comparison of these with the present work will not be attempted as the degree of accuracy in the latter is far greater. The conclusion that there is no effect of current upon copper other than that caused by temperature can be accepted to an accuracy of less than 1 per cent.

An interesting comparison regarding the history effect and the magnitude of change with temperature is furnished by the work of Shakespeare,[1]

[1] Loc. cit.

who used interference methods to determine the modulus at 13° C. and at 100° C. He does not compute the value of the modulus but gives the change from 13° C. to 100° C. as 3.6 per cent. For this range the present specimen shows a change of 5 per cent. Shakespeare also found that the modulus increased with continued heating and cooling, until a permanent state was reached. The first heating produced a sudden increase of several per cent. which was followed by a gradual change. Nine heatings produced a total increase of 12 per cent. The permanent change described in this paper was of the same kind and amounts to 7 per cent.

In the following comparison of results upon the temperature effect the bracketed figures are taken from our own curves. At 20° C. our value of Young's modulus was 11.5×10^{11} dynes per cm^2. Miss Noyes[1] found the modulus of a specimen of copper to be 12.02 at 20° C. This and another specimen tested at temperatures up to 150° C. gave a uniform decrease of the modulus which computed for 20° C. to 140° C. gives a change of 8.5 per cent. and 16 per cent. respectively [10 per cent.]. At 17.4° C. Gray, Blyth, and Dunlop[2] found the modulus of a sample of commercial copper to be 11.15 and of hard drawn electrolytic copper at 19.5° C. to be 12.9. They made tests over a range of 100° C. and reported a uniform rate of decrease which computed for 20° C. to 100° C. gives for the two samples changes of 1.2 per cent. and 3.4 per cent. respectively [4.6 per cent.].

Slotte[3] found for two specimens changes of 6.6 per cent. and 4.2 per cent. respectively [1.5 per cent.], for a temperature increase from 20° C. to 60° C. The moduli at 20° C. were respectively 12.4 and 12.7. The more important point is that he did not find a uniform rate of change. The modulus of the former specimen decreased at an increasing rate while the latter shows a decrease at a decreasing rate. Decrease of the modulus at an increasing rate is also indicated by the work of Wertheim.[4] If his results at 15° C., 100° C., and at 200° C. are plotted and a smooth curve drawn it is almost identical with our own curves, except that the values are about 10 per cent. lower. Regarding the nature of the change observations on the torsion modulus are valuable although too great stress must not be placed on them. Kohlrausch and Loomis[5] made observations upon copper at various temperatures. They found an increasing rate of change as the temperature increased. Computed for 20° C. to 100° C. the change is 4.2 per cent. [4.7 per cent.], and for 20° C. to 140° C. 7.5 per cent. [10 per cent.]. Slotte[6] has also made a study

[1] Loc. cit. [2] Loc. cit. [3] Loc. cit.
[4] Loc. cit. [5] Loc. cit. [6] Loc. cit.

of the torsion modulus of copper and finds the same increasing rate of change. Corresponding values from his work are 5.9 per cent. and 8.3 per cent.

The results that have been cited must be considered from two standpoints, first as to the general nature of the changes of Young's modulus, whether uniform or otherwise, and secondly, regarding the numerical values.

Examination of the methods of those who have reported a uniform decrease shows that their work was not of sufficient accuracy to have detected the variation from a linear relation found by others. We are not certain how much importance should be attached to the work of Slotte upon Young's modulus. He worked also with aluminum, iron, and platinum as well as copper and found a decreasing rate of change. None of these results seem to have been repeated. The torsion modulus can be determined to a much higher degree of accuracy and Slotte's recent work upon the torsion modulus of all these metals shows an increasing rate of change. Since the evidence that is available points toward a similarity in the nature of the temperature change of the two moduli this raises a question as to whether Slotte's former results upon Young's modulus are a true temperature effect.

With the results of Wertheim and of Slotte upon one specimen agreeing with our own and the work of Kohlrausch and Loomis and of Slotte upon the torsion modulus showing the same general type of change, I believe that the conclusion that Young's modulus of copper decreases with increase of temperature at an increasing rate has sufficient corroboration.

A comparison of the numerical values of Young's modulus and of the temperature coefficient, ample allowance being made for experimental error, leaves no doubt as to the importance of chemical purity, method of preparation, and size of specimen. It is possible that samples of copper may be found that will show effects peculiar to current heating, or will not give modulus-temperature curves of the simple form that I have found, but I am inclined to believe the main differences will be found in the magnitude of the coefficients. Undoubtedly further work will reveal some relation between the chemical composition, the coefficient of linear expansion, the electrical conductivity, and other physical constants, and the value of Young's modulus and its rate of change with temperature. Investigation is under way upon other metals in order to study the effect of current, to determine the temperature coefficient of Young's modulus, and to study the relation between the temperature changes of the two elastic moduli.

In conclusion I wish to acknowledge indebtedness to the staff of the physical laboratory of the State University of Iowa for their interest in the work and especially to Professor G. W. Stewart for suggesting the problem and to Professor J. N. Pearce, of the department of chemistry, for the chemical analysis.

PHYSICAL LABORATORY
STATE UNIVERSITY OF IOWA,
August, 1913.

THE EFFECT OF SPACE CHARGE AND RESIDUAL GASES ON THERMIONIC CURRENTS IN HIGH VACUUM.

BY IRVING LANGMUIR.

WHEN a carbon or metal filament is heated in a vacuum and surrounded by a positively charged metal cylinder, it is well known that electrons are given off by the hot solid. This effect in lamps has been commonly known as the Edison effect and has been rather fully described in the case of carbon lamps by Fleming.[1]

Richardson and others have studied quantitatively the ionization produced by hot solids, especially from heated platinum, and have collected a large amount of data. It has generally been found that the saturation current is independent of the pressure of the gas and increases rapidly with increasing temperature of the filament. However, certain gases were found to have very marked effects; for example, traces of hydrogen were found to enormously increase the saturation current obtained from hot platinum.[2] Recent investigations have shown[3] that at least in some cases the current is due to secondary chemical effects.

Pring and Parker[4] showed that the current obtained from incandescent carbon could be cut down to very small values by progressive purification of the carbon and improvement of the vacuum. They conclude that "the large currents hitherto obtained with heated carbon cannot be ascribed to the emission of electrons from carbon itself, but that they are probably due to some reaction at high temperatures between the carbon, or contained impurities, and the surrounding gases, which involves the emission of electrons." Pring and Parker observed also that the ionization (or rather thermionic current) "increased only very slightly with the temperature above 1800°."

The effect of these publications, together with that of Soddy,[5] who noticed similar effects with a Wehnelt cathode, has been to cast doubt on the existence of a thermionic current in a perfect vacuum and from pure metals. The opinion seems to be gaining ground, especially in Germany,

[1] Phil. Mag., *42*, p. 52 (1896).
[2] H. A. Wilson, Phil. Trans., *202*, 243 (1903).
[3] Fredenhagen, Ver. d. phys. Ges., *14*, 384 (1912).
[4] Phil. Mag., *23*, 192 (1912).
[5] Nature, *77*, 53 (1907).

that the emission of electrons from incandescent solids is a secondary effect produced by chemical reactions, or at least is caused by the presence of gas.

With the above-mentioned exceptions, it has generally been found that the thermionic current increased with the temperature at a very high rate. The relation between current and temperature was usually accurately represented by Richardson's equation

$$i = a\sqrt{T}\,e^{-\frac{b}{T}}, \tag{1}$$

where a and b are constants and i is the saturation current at the absolute temperature T.

If the older values of a and b as found, for example, for carbon, are substituted in the above equation and the currents for very high temperatures (above 2500°) are calculated, values of many amperes or even thousands of amperes per square cm. are usually obtained. This raises the question why in ordinary incandescent lamps very large thermionic currents do not occur.

There is every reason to think that the thermionic current from tungsten should be fairly large. When we run a tungsten lamp up to 2 or even 2.5 times its normal voltage (filament temperature 2900–3400° K.) we should therefore expect to get thermionic currents of several amperes between the two ends of the filament. Simple observation of a lamp run under such conditions indicates that this is not the case. For example, consider a lamp which takes 110 volts and 0.3 ampere when running at normal specific consumption (1.25 watts per candle). By raising the voltage to 250, the temperature of the filament will be brought to about 3000° K. and the current is then about 0.45 ampere. The resistance of the filament has thus increased from 366 ohms up to 555. The total surface of the filament is nearly half a square cm., yet it is evident that if there is any thermionic current between the two ends of the filament, it cannot exceed a few hundredths of an ampere. This apparent discrepancy between the results of calculation by Richardson's equation and the facts observed with a tungsten lamp seemed at first to confirm the growing opinion that in a very high vacuum the thermionic current is very small, if not entirely absent.

Experiments on the Edision effect in tungsten lamps, made some time ago by the writer, throw a great deal of light on the cause of the apparent failure of Richardson's equation at high temperatures. The observations therefore seem of sufficient interest to warrant their publication.

EXPERIMENTS ON EDISON EFFECT IN TUNGSTEN LAMPS.

Some lamps were made containing two single loop (hairpin) tungsten filaments with separate leading-in wires. Each loop could thus be run separately. The lamps were given a specially good lamp exhaust, which involved heating them to 360° for an hour while being exhausted with a mercury pump. A trap immersed in liquid air was placed between the pump and the lamp to condense out water vapor, carbon dioxide and mercury vapor. The filaments were then connected in series and the lamps run at a specific consumption of about 1 watt per candle for fifteen minutes, to drive the gas from the filaments. The lamps were then sealed off from the pump and the filaments were again heated, this time being run at 0.4 watt per candle for a few minutes, to age the filaments and improve the vaccuum (clean-up effect).

Experiments were then undertaken to measure the thermionic currents that flowed across the space between the two filaments when one was heated to various temperatures while the other was connected to a constant source of positive potential of about 125 volts. A milliammeter was connected in series with the cold filament.

When the temperature of the cathode filament was raised to about 2000° K. a current of about 0.0001 ampere was observed to flow between the two filaments. As this temperature was raised the thermionic current rose very rapidly, until at about 2200° K. it was about .0006 ampere. As the temperature was raised above 2200° K., *no further increase in the thermionic current occurred*, even when the filament was heated nearly to the melting-point (3540° K.). By raising the voltage on the anode to about 250 volts, the thermionic current increased to about .0015 ampere. It required, however, a temperature about 200° higher to reach this current than had been found necessary to reach the maximum current at the lower voltage. At temperatures below 2200° K., the current was practically the same with 125 as with 250 volts.

The results of a later and more accurate experiment are given in Fig. 1. The filament used for these measurements consisted of a single loop of drawn tungsten wire, of diameter .0069 cm. and total length of 10.84 cm. and area of 0.234 sq. cm. A similar filament, at a distance of about 1.2 cm., served as anode. Both filaments had been aged a couple of hours at high temperature and the vacuum thus obtained was certainly better than 10^{-6} mm.[1]

The temperatures of the filament were determined from the relation

$$T = \frac{11{,}230}{7.029 - \log_{10} H},$$

[1] Judging from measurements on similar lamps made by means of the "molecular" gage described by the writer, PHYS. REV., 1 (2), 337 (1913).

where H is the intrinsic brilliancy of the filament in international candles per sq. cm. of projected area.[1]

The points indicated by small circles (Fig. 1) are experimentally determined. Two different anode voltages were used: 240 and 120 volts, with respect to the negative terminal of the filament which served as hot cathode. The voltage used to heat the cathode varied from about 7 to 15 volts, so the *average* potential difference between anode and cathode

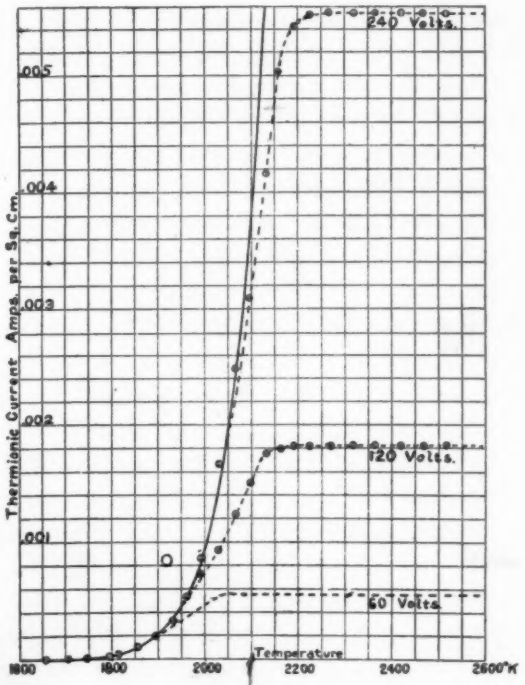


Fig. 1.

was somewhat less than 240 and 120 volts. The curve given for 60 volts was determined from other experiments devised especially to determine the effect of voltage variations.

It is seen from these curves that at low temperatures the current for all three voltages is the same, but that as the temperature is raised the currents at the lower voltages fall below those for higher voltages and finally each in turn reaches a constant value.

By plotting (log. $i - \frac{1}{2} \log T$) against $1/T$ it was found that all the points on the 240-volt curve up to a temperature of about 2150° lay very close to a straight line. This indicates that these results can be expressed

[1] The derivation of this formula will soon be published, probably in the PHYSICAL REVIEW.

by Richardson's equation. From the slope and position of the line, the values of a and b of Richardson's equation were found to be

$$a = 27 \times 10^6 \text{ (amperes per sq. cm.)},$$
$$b = 55{,}600 \quad \text{(degrees)}.$$

The heavy black curve of Fig. 1 was calculated by plotting Richardson's equation, using these values of a and b. The agreement between this curve and the experiments at low temperature is nearly perfect; in fact, much better than can be seen from Fig. 1.

It is seen that each experimentally determined curve can be divided into three parts:

1. A part which follows Richardson's equation accurately.
2. A part which consists of a horizontal straight line; that is, a part in which the current is independent of the temperature of the filament.
3. A transition curve between these.

The horizontal part of the curve was of particular interest. The current being independent of the temperature of the filament is probably independent of the nature of the cathode. It seemed possible, however, that it might be dependent on the anode. Several experiments were undertaken to determine the factors which governed the value of this new kind of "temperature" saturation current. It was found that it was very largely affected by any one of the four factors:

1. Voltage of anode.
2. Presence of magnetic field.
3. Area of anode.
4. Distance from anode to cathode.

It is especially noteworthy that none of these factors had any influence on the thermionic current over the first part of the curve; *i. e.*, that part which follows Richardson's equation. That is, the constants a and b were not affected by voltage, or magnetic field or distance or area of anode.

After trying out several hypotheses which suggested themselves, it finally occurred to the writer that this temperature saturation might be due to a space charge produced by the electrons between the cathode and anode. The theory of electronic conduction in a space devoid of all positive charges or gas molecules seems to have been strangely neglected. It has apparently always been taken for granted that positive ions are present, or at least a sufficient amount of gas, so that the motion of the electrons follows the laws of diffusion. J. J. Thomson[1] gives the differential equations that apply to the calculation of electron conduction

[1] Conduction of Electricity through Gases, 2d edition, p. 223.

through space, and suggests that a method for the determination of e/m could be worked out in this way. He apparently does not fully integrate the equations or realize their application to ordinary thermionic currents.

Theory of Electronic Conduction in a Space Devoid of Molecules or Positive Ions.

In order to form a clear conception of the problem before us, let us consider (see Fig. 2) two infinite parallel planes, A and B, one of which, A, has the properties of an incandescent solid; that is, we assume that it emits low velocity electrons spontaneously. The other, plane B, we consider to be positively charged.

Now if the temperature of the plate A is so low that few or no electrons are emitted, then the potential between the two plates will vary linearly between the two, as indicated by the line PT.

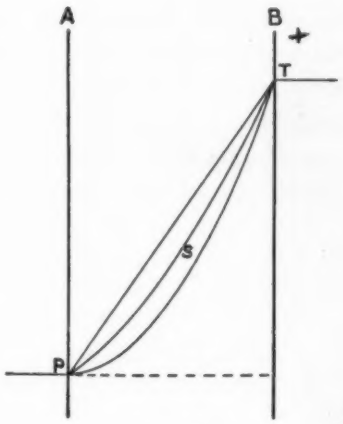


Fig. 2.

As the temperature of A is raised, electrons are emitted. Under the influence of the field these pass across the space from A to B and thus constitute a current of magnitude i (per sq. cm.).

These electrons move with a velocity which depends on the potential drop through which they have passed. Let us assume, as a first rough approximation, that they move with constant velocity across the space. Then there will be in the unit volume a space charge ρ equal to i/v, where v is the velocity of the electrons. If the velocities are uniform, the space charge will be uniform and it follows from Laplace's equation

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = -4\pi\rho \tag{2}$$

that

$$\frac{d^2 V}{dx^2} = -4\pi\rho. \tag{3}$$

If we consider ρ constant and negative (for electrons), we see from this equation that the potential distribution between the two plates takes the form of a parabola, as indicated by the curve PST.

If the temperature of the plate A be increased still further, the electron current increases so that the potential curve finally becomes a parabola with a horizontal tangent at P.

If we assume that the electrons are given off from the plate A with practically no initial velocity, we see that the current cannot increase beyond the point where the potential curve becomes horizontal at P, for any further increase of current would make the potential curve at P slope downwards and the electrons would be unable to move against this unfavorable potential gradient.

In other words, we see that the effect of the space charge is to limit the current. A further increase in the temperature of the plate A would then not cause an increase of current.

Electron Current between Parallel Planes.—Let us now attempt a more rigorous solution of the problem.

It has been shown by Richardson and others that the mean kinetic energy of the thermions is closely equal to that of gas molecules at the same temperature. This indicates that they have velocities so low that very few of them are capable of moving against a negative potential of more than a couple of volts. Since the voltages applied to the anode are much larger than this, we may assume, for convenience, that the electrons are given off by the plate A without initial velocity.

Now let V be the potential at a distance x from the plate A. The kinetic energy of an electron when it has traveled the distance x from the plate will thus be

$$\tfrac{1}{2}mv^2 = Ve. \tag{4}$$

The current (per unit area) carried by the electrons at any place will be

$$i = \rho v. \tag{5}$$

For convenience, we take e and ρ positive even for electrons. Equation (3) thus becomes (in electrostatic units)

$$\frac{d^2V}{dx^2} = 4\pi\rho. \tag{6}$$

These three equations enable us to express V as a function of x and i. By eliminating ρ and v from (4), (5) and (6), we obtain

$$\frac{d^2V}{dx^2} = 2\pi\sqrt{2}\sqrt{\frac{m}{e}}\frac{i}{\sqrt{V}}. \tag{7}$$

Multiply this by $2\cdot dV/dx$ and integrate

$$\left(\frac{dV}{dx}\right)^2_{x=x} - \left(\frac{dV}{dx}\right)^2_{x=0} = 8\pi i\sqrt{\frac{2mV}{e}}. \tag{8}$$

Now if there is an opposing (negative) potential gradient at the surface of the plate A, *no current* will flow. If there is a positive potential

gradient all the electrons that are given off from the plate A will reach B, so that the current that flows will be determined by Richardson's equation. The case that we are interested in is that in which the current is less than the saturation current and is determined by the voltage of the anode. Evidently for this case the potential gradient at the plate A is zero; that is,

$$\left(\frac{dV}{dx}\right)_0 = 0,$$

whence from (8) by extracting the square root:

$$\frac{dV}{dx} = \sqrt{8\pi i}\sqrt[4]{\frac{2mV}{e}}. \tag{9}$$

Integrating and solving for i, we obtain:

$$i = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{x^2}. \tag{10}$$

This equation[1] gives the maximum electron current density between two infinite parallel plates with the distance x between them and with a potential difference V. This equation holds only where the initial velocity of the electrons at the plate A is negligible compared to that produced by the potential V. It does not hold at such high voltages that the electrons move with velocities approaching that of light.

Taking $e/m = 1.77 \times 10^7$ E.M. units, reducing to E.S. units and substituting in (10) and then reducing to volt, ampere units, we obtain from equation (10):

$$i = 2.33 \times 10^{-6}\frac{V^{\frac{3}{2}}}{x^2}, \tag{11}$$

where i is the maximum current density in amperes per sq. cm., x is the distance between the plates in centimeters, and V is the potential difference in volts.

Electron Current between Concentric Cylinders.—Let us consider a wire of radius a placed in the axis of a cylinder of radius r. Let i be the thermionic current per unit of length from the wire.

For the case of symmetrical cylindrical coördinates, Laplace's equation becomes[2]

$$\Delta V = \frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right) = 4\pi\rho.$$

[1] Since submitting this paper for publication the attention of the writer has been called to the fact that C. D. Child (PHYS. REV., *32*, 492, 1911), has already derived this equation. He has, however, applied it only to the case where the conduction takes place solely by positive ions.

[2] Weber's Differential Gleichungen, 1900, Vol. 1, p. 98.

or

$$\frac{d}{dr}\left(r\frac{dV}{dr}\right) = 4\pi\rho r. \tag{12}$$

The equation corresponding to (5) is

$$i = 2\pi r\rho v. \tag{13}$$

These two equations, together with equation (4), which also applies to this case, give us

$$r\frac{d^2V}{dr^2} + \frac{dV}{dr} = i\sqrt{\frac{2m}{eV}}. \tag{14}$$

This equation probably cannot be directly integrated, but it is possible to obtain a result in terms of a series. The final solution takes the form

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{r\beta^2}, \tag{15}$$

where β is a quantity which varies from 0 to 1. The value of β can be obtained by substituting equation (15) in (14) and placing

$$r = ae^{\gamma}. \tag{16}$$

Equation (14) is thus reduced to

$$3\beta\frac{d^2\beta}{d\gamma^2} + \left(\frac{d\beta}{d\gamma}\right)^2 + 4\beta\frac{d\beta}{d\gamma} + \beta^2 - 1 = 0. \tag{17}$$

The solution of this equation gives

$$\beta = \gamma - \tfrac{2}{5}\gamma^2 + \tfrac{11}{120}\gamma^3 - \tfrac{47}{3300}\gamma^4 + \cdots, \tag{18}$$

where

$$\gamma = ln\frac{r}{a}.$$

Mr. E. Q. Adams, of this laboratory, has calculated the values of β for various values of r/a and has shown that the value of β rapidly approaches unity and that for all values of r/a greater than 10, β may for most purposes be taken equal to unity. The following table was prepared from Mr. Adams' data:

TABLE I.

r/a	β^2	r/a	β^2
1.00	0.000	5.0	0.755
1.25	0.045	6.0	0.818
1.50	0.116	7.0	0.867
1.75	0.200	8.0	0.902
2.00	0.275	9.0	0.925
2.50	0.405	10.0	0.940
3.00	0.512	15.0	0.978
4.00	0.665	∞	1.000

Since in practical cases the diameter of the cylinder around the wire is usually much more than ten times that of the wire, the formula (15) may usually be written

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{r}. \tag{19}$$

That is, the maximum electron current from a small wire is independent of the diameter of the wire, inversely proportional to the radius of the enclosing cylinder and proportional to $V^{\frac{3}{2}}$.

Substituting numerical values for e/m and reducing to ordinary electrical units (volts, amperes, cm.) equation (19) becomes

$$i = 14.65 \times 10^{-6}\frac{V^{\frac{3}{2}}}{r}. \tag{20}$$

Electron Current between Electrodes of Other Shapes.—It can be shown that between electrodes of any shape the maximum electron current varies with $V^{\frac{3}{2}}$. Let us consider a system in which we have the maximum electron current with the potential difference V. Then Laplace's equation

$$\Delta V = 4\pi\rho \tag{2}$$

holds for such a space, as well as the two equations

$$i = \rho v \tag{5}$$

and

$$\tfrac{1}{2}mv^2 = Ve. \tag{4}$$

Now let us increase the voltage in the ratio $1 : n$ and increase the current in the ratio $1 : n^{\frac{3}{2}}$. Equations (5) and (4) thus become

$$n^{\frac{3}{2}}i = \rho v,$$

$$\tfrac{1}{2}mv^2 = nVe.$$

Eliminating v from these, and solving for ρ, we get

$$\rho = ni\sqrt{\frac{m}{2Ve}}.$$

From this we see that ρ has been increased n fold. However, since V has been increased also n fold, Laplace's equation (2) still holds. Hence we see that increasing the current by a factor $n^{\frac{3}{2}}$ and increasing the voltage by the factor n, leads to a condition which still satisfies the three equations (2), (4), and (5). This is, however, equivalent to increasing the current proportionally to $V^{\frac{3}{2}}$. We thus see that whatever the configuration of the electrodes, the *maximum* electron current varies with $V^{\frac{3}{2}}$.

DISCUSSION OF THE THEORY.

The foregoing theoretical considerations have indicated that in a space devoid of positive ions, or gas molecules, the space charge caused by the electrons limits the current that flows between a hot cathode and cold anode under a given difference of potential. It now remains to compare the maximum currents obtained in the experiments, with those calculated from the equations that have been derived.

Let us consider the data given in Fig. 1. The maximum electron current at 120 volts was .000426 ampere from the hot filament, or .00182 ampere per sq. cm. At 240 volts the total current was .00130 ampere, or .00556 ampere per sq. cm. Since we are not dealing with parallel plane electrodes, nor with concentric cylinders, neither equation (11) nor (20) will apply rigorously. We are, however, mainly concerned in determining whether the space charge is an adequate explanation of the observed limitation of the thermionic current, and therefore can test out the two equations by calculating the distances which would have to exist between plane or cylindrical electrodes in order to give the observed thermionic currents.

We will first test out equation (11), which should apply to parallel plane electrodes. Let us take the observed values of V and i and calculate x. We thus obtain:

For $V = 120$ volts and $i = .00182$, we find $x = 1.30$ cm.;

$V = 240$ volts $\quad i = .00556$, we find $x = 1.25$ cm.

Our formula thus indicates that the current density between parallel plane electrodes about 1.3 cm. apart would be the same as that observed. This is, however, very close to the actual distance between the electrodes. The very close agreement is probably due to the counter-balancing of two factors: first, the weakening of the electrostatic field, due to the flare of the lines of force around the wires, and second, the reduction of the intensity of the space charge owing to this same flare.

Let us now test the equation (20), which should apply to concentric cylinders. Since the wire was 10.8 cm. long, the values of i (amperes per cm.) were .0000394 at 120 volts and .000120 at 240 volts. Substituting these values in (20) and solving for r we obtain

at 120 volts $r = 490.$ cm.,

240 volts $r = 450.$ cm.

We see that the radius of a cylindrical anode would have to be very large (470 cm.), in order to give only the observed thermionic current. This result, however, appears perfectly reasonable, for the field produced

by a small wire anode is naturally much weaker than that produced by a cylindrical anode surrounding the cathode.

The numerical values obtained from these equations are certainly of the right order of magnitude and agree as well with the experimental results as could be expected when the shape of the electrodes departs so far from those assumed in the calculations.

We have seen that the theory leads us to the conclusion that for electrodes of any shape the maximum thermionic current should vary with $V^{\frac{3}{2}}$. This can be readily tested out from the experiment. The ratio of the currents at the two voltages is 3.05. Taking the 2/3 power of this ratio, the voltage ratio should be 2.10, whereas actually it was 2.0. However, it must be remembered that the voltage of the anode was measured from the negative end of the filament, so that the average voltage drop from anode to cathode was about seven or eight volts less than those given. This would give for the voltage ratio 232 : 112, or 2.07, as against the 2.10 calculated by the three-halves power law.

Several experiments have been undertaken to study the relation of maximum current to voltage over a wide range of voltage. Voltages from 10 volts up to 800 volts have been tried and the results plotted on logarithmic paper. From the slopes of the resulting lines the exponent of the voltage was calculated. Values varying from 1.5 to 1.7 have been obtained. Under certain conditions, to be described in more detail later, values much higher than these are sometimes obtained.

The above considerations indicate that the space charge produced by the electrons is a sufficient cause for the limitation of current observed in the experiments.

Effect of Residual Gases on Constants of Richardson's Equation.

In some of the early experiments on the thermionic current between two tungsten filaments, extremely variable results were obtained for the constants of Richardson's equation. In many cases, however, when anode potentials as high as 150 or 250 volts were applied, a blue glow appeared in the lamp, indicating ionization of the residual gas. To get rid of this, the two filaments were connected in series and both heated to a very high temperature (2900° K.) for a few minutes. This "cleans up" the vacuum to an extremely high degree. The writer is publishing a series of articles in the Journal of the American Chemical Society on the clean up of various gases in a tungsten lamp. It has been found that with a very high temperature of the filament, all gases except the inert ones may be removed practically quantitatively. This treatment of the lamp to improve the vacuum resulted in a marked change in the

constants of Richardson's equation and also changed the maximum thermionic currents.

To still further improve the vacuum in some cases, the entire bulb was immersed in liquid air and the filaments were again heated to high temperature for a short time. This sometimes resulted in a further change in the thermionic current.

These effects were clearly due to traces of residual gas. To study them in more detail, some experiments were carried out in which lamp bulbs containing two filaments (or sometimes three) were connected to a vacuum system consisting of Töpler pump, sensitive McLeod gage and trap immersed in liquid air, placed directly below the lamp. The lamps were exhausted to less than .0001 mm. and heated for one hour to 360° C., to drive water vapor and carbon dioxide into the liquid air trap. No stop-cocks were used in the entire system, so that vapors of vaseline, etc., were avoided. The liquid air trap prevented the entrance of mercury vapor into the lamp. Care was taken to keep liquid air on the trap day and night during the whole experiment.

The lamp bulb was about 3.5 cm. diameter and was connected to the rest of the vacuum system by a tube attached at the top of the bulb and bent into a goose neck. In this way the bulb could be immersed completely in liquid air if desired.

After exhaustion of the bulb and ageing of the filament at high temperature, a run was made with 177 volts on the anode, but without liquid air on the bulb. The pressure, according to the McLeod gage, was .00012 mm.

The constants of Richardson's equation were found to be

$$a = 22.10^6 \text{ amps. per sq. cm.},$$

$$b = 55{,}800 \text{ degrees.}$$

Liquid air was now placed around the lamp bulb, and the thermionic current again determined. During this run the pressure was constant at .00007 mm.

The constants were then found to be:

$$a = 34 \times 10^6,$$

$$b = 55{,}500.$$

A plot of the curve, calculated from these data by Richardson's equation, is given in Curve I., Fig. 3, together with the experimentally determined points (Curve III.).

The effect of cooling the bulb in liquid air was thus to increase the thermionic current considerably (about 60 per cent. at 2000° K.). The

filament was now run at 2130° K., at which temperature a thermionic current of .00214 amp. was observed. The liquid air was then removed from the bulb. The thermionic current fell rapidly to .00049 and then rose to .00184, at which it remained steady.

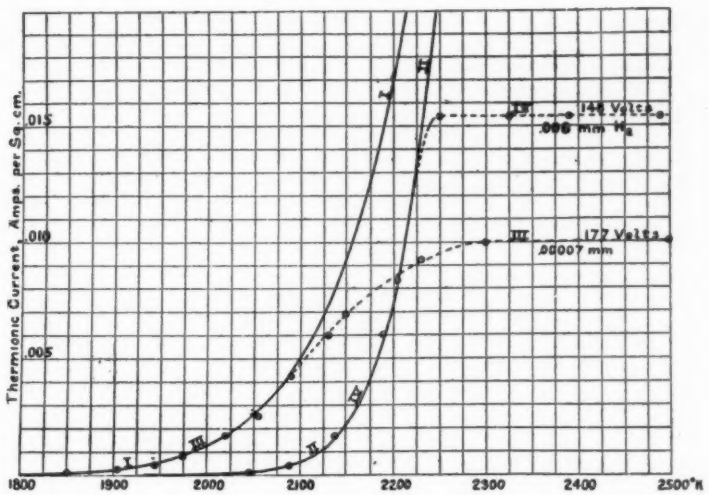


Fig. 3.

Hydrogen.—Pure hydrogen to a pressure of .012 mm. was now admitted. The thermionic current was rather variable, changing gradually with the time, but by running the temperature up and down several times, fairly consistent results were obtained. The average values of Richardson's constants were

$$a = 5.4 \times 10^{11},$$

$$b = 82{,}500.$$

The hydrogen had gradually cleaned up during these runs from 0.012 mm. to .006 mm.[1] The remainder of the hydrogen was now pumped out (down to .00011 mm.) and another run was made to determine the thermionic current in good vacuum. The results were

$$a = 4.3 \times 10^{12},$$

$$b = 85{,}000.$$

The pressure rose during this run from .00011 to .00052 mm.

The removal of the hydrogen thus produced relatively little effect, and certainly did not tend to cause a and b to return to the original values in a good vacuum.

[1] See paper on Active Modification of Hydrogen, Langmuir, J. Amer. Chem. Soc., *34*, 1310 (1912).

More hydrogen (.007 mm.) was now let in, and the constants were found to be

$$a = 7.6 \times 10^{18},$$

$$b = 115{,}000.$$

During this run the hydrogen cleaned up from .007 to .004 mm.

A plot of the curve calculated from Richardson's equation is given in Fig. 3 (Curve II.), together with the experimentally determined points (Curve IV.).

The general effect of the hydrogen had apparently been to permanently lower[1] the thermionic current, especially at low temperature. It had at the same time increased the value of the constant b to more than double its original value.

Effect of Bulb Temperature.—At this stage in the experiments it was found that touching the bulb with the fingers had a marked effect on the thermionic current. This was due to a temperature effect. With the filament at 2190° K. the current was .0011 amp. Warming the bulb slightly lowered the current to .0003. Placing ice water around the bulb raised the current to .0038. Liquid air, however, gave the same result as ice water. A run with the bulb in liquid air, with a pressure of .00025 mm. of hydrogen in the bulb, gave

$$a = 20.4 \times 10^{6},$$

$$b = 55{,}600.$$

These values are very close to those previously obtained with liquid air before any hydrogen had been let into the bulb.

Immediately after this run a beaker containing water at 62° C. was placed around the bulb. The pressure rose to .0017 mm. and the values of a and b became

$$a = 7.7 \times 10^{16},$$

$$b = 105{,}000.$$

A large number of runs were now made at different bulb temperatures. The results were similar to those already given, except that gradually the effect of heating the bulb became less marked and after a couple of days practically the same results were obtained with the bulb at 50° as at 0°. For example, two consecutive runs gave

$$\text{at } 0° \quad a = 54.10^{6}, \quad b = 58{,}500;$$

$$\text{at } 53° \quad a = 60.10^{6}, \quad b = 58{,}500.$$

[1] The increase in the value of b in Richardson's equation much more than offsets the increase in a, so that at temperatures in the neighborhood of 2000°, the currents in hydrogen are very much smaller than the original currents in vacuum.

Before this condition of insensitiveness to bulb temperature had been reached, tests were made to see if the changes in the thermionic current were due to vacuum changes or absorption of gas by the filament. The effect of interchanging the two filaments was tried many times. That is, the filament which had previously been used as anode was made cathode and vice versa. In no case did this change make any material difference in the magnitude of the thermionic current. The heating of the bulb produced exactly the same effect, regardless of the previous history of the filament. The changes that did occur could clearly all be ascribed to vacuum changes caused by the absorption or evolution of gas by the bulb.

Water Vapor.—The fact that the temperature of the bulb was in some cases so much more important than the pressure of hydrogen indicated that it was the presence of water vapor that caused the decrease in the thermionic current and the increase in b. To test this out, the liquid air was removed for a couple of minutes from the liquid air trap below the lamp and then replaced. The effect of thus allowing water vapor to enter the lamp was to make the thermionic current extremely sensitive to the temperature of the bulb. This sensitiveness could be destroyed again by heating the bulb to 360° and cooling.

The conclusion to be drawn from these facts is that the decrease in the thermionic current is due to the presence of traces of water vapor. The McLeod gage gives no indication of such small amounts of water vapor, but the fact that little or no hydrogen is evolved by the action of the filament on the water vapor, together with the fact that the water vapor can remain days in the lamp before diffusing down into the liquid air trap, indicate that the pressure must be extremely low—probably not over 10^{-6} mm. Yet the evidence is strong that such pressures of water vapor have an enormous effect on the saturation thermionic current from tungsten.

Oxygen.—It had been known that water vapor in contact with a hot tungsten filament oxidizes the filament with the liberation of atomic hydrogen. It was therefore of interest to know whether the marked effect produced on the thermionic current by water vapor is due to this particular reaction or whether the same effect will not be produced by dry oxygen.

To test this out, the system was exhausted to a pressure of .00012 mm. The mercury in the Töpler pump bulb was raised so as to seal off the bulb and pure dry oxygen was admitted to the bulb. The quantity was chosen so that it would give a pressure of .005 mm. when allowed to flow out into the whole system by lowering the mercury in the pump bulb.

The filament (*A*) was now run at 2190° K., and the other filament (*B*) was charged 250 volts positively with respect to the cathode. The thermionic current was .0031 amp.

On lowering the mercury in the pump bulb and allowing the oxygen to enter the lamp bulb, the thermionic current dropped immediately to .00013; that is, to 4 per cent. of its original value. As the oxygen gradually disappeared, the current steadily rose in value, as follows:

	Pressure, Mm.	Thermionic Current.
On admitting oxygen.....	.005	.00013
After 5 minutes.....	.0003	.00030
After 10 minutes.....	.00016	.00090
After 15 minutes.....	.00014	.00164
After 20 minutes.....	.00010	.00230
After 28 minutes.....	.00007	.00270

After letting in another supply of oxygen, the thermionic current was determined at various temperatures and gave

$$a = 6.8 \times 10^{13},$$

$$b = 94{,}300.$$

The effect of oxygen is thus found to be quite similar to that of water vapor.

Nitrogen.—Experiments with nitrogen showed that this gas also usually decreased the thermionic current, although not so strongly as oxygen. Since nitrogen does not clean up as rapidly as oxygen, this gas was chosen for a series of experiments to determine whether other factors, such as anode voltage, had an influence on the Richardson constants in the presence of gas.

Effect of Anode Potential.—In one experiment a pressure of about .001 to .002 mm. of nitrogen was present in the bulb. A run was made with a potential of 220 volts on the anode, then a run with 100 volts, and then another run at 220 volts. The thermionic currents (milliamperes per sq. cm.) in the three runs were as follows:

TABLE II.

Temp.	220 Volts.	100 Volts.	220 Volts.
2045	.....	0.34	0.29
2090	.....	0.70	0.63
2140	.....	1.54	1.29
2190	2.7	4.0	2.9
2250	6.3	4.9	7.0
2325	16.2	5.0	19.3
2390	21.0	5.0	20.0
Pressure of N_2 =	.0015 mm.	.0012 mm.	.0012 mm.

These results show that under certain conditions (low temperature and proper pressure of nitrogen) less current is obtained with 220 volts than with 100 volts. In this connection it may be said that these thermionic currents were reproducible and accurately measurable. The values changed gradually, however, as the nitrogen cleaned up.[1]

The following are typical runs (Table III.) selected from many that were made while the nitrogen was gradually disappearing:

TABLE III.

Temp.	Pressure .00067 Mm.		Pressure .00011 Mm.	
	100 Volts.	220 Volts.	100 Volts.	220 Volts.
2045	0.53	0.36	1.58	1.50
2090	1.02	0.86	2.9	2.90
2140	2.50	1.90	3.8	6.2
2190	4.2	4.50	4.4	9.8
2250	4.6	11.8	4.6	11.4
2325	4.8	13.8	.....	11.8
2390	.....	13.9	.....	12.1

Thus, as the nitrogen cleans up, the thermionic current increases and tends to return to its original value. At the same time the peculiar effect of the anode voltage in causing less current to flow at high voltage also practically disappears.

All the experiments with nitrogen were made with the bulb surrounded with ice. This precaution, however, did not seem necessary in these runs, for at various times the ice was removed, but the thermionic current remained unchanged.

In order to investigate in more detail the effect of the anode potential at various pressures of nitrogen and different filament temperatures, a special experiment was undertaken. A lamp containing two single loop filaments in a large bulb was sealed to the same vacuum system and exhausted as before. The filaments were of .0124 cm. diameter and each 8.9 cm. long.

After ageing the filament, the thermionic current was measured at 120 and 230 volts; the constants a and b were:

$$\text{at 120 volts} \quad a = 1.2 \times 10^{13}, \quad b = 83{,}000;$$

$$230 \quad " \quad a = 4.7 \times 10^{12}, \quad b = 80{,}500.$$

On the average, even with currents so low that the space charge should have no effect, the thermionic current was about 20 per cent. less with

[1] This is the electrochemical clean-up of nitrogen referred to by the writer in a paper on "The Clean-up of Nitrogen in Tungsten Lamps," Jour. Amer. Chem. Soc., *35*, 931 (1913).

120 than with 230 volts. This effect, which is just the opposite of that noted in the preceding experiment, is of fairly common occurrence when very special precautions are not taken to avoid traces of certain gases.

The effect of oxygen on the thermionic current with different anode potentials was next tried. In every case the current was greatly reduced by the presence of this gas. The currents obtained with 120 volts and with 230 volts were always practically identical.

Another measurement of the thermionic current in good vacuum (.0001 mm.) at 120 and 240 volts gave

$$a = 1.1 \times 10^{11},$$

$$b = 74{,}000.$$

The curve obtained by Richardson's equation with these constants is given in Curve I., Fig. 4, while Curves II. and III. are drawn through the experimentally determined points.

A pressure of 0.0021 mm. of nitrogen was now introduced and the following measurements made at 120 and 235 volts. The results are expressed in milliamperes per sq. cm.

TABLE IV.

Filament Temp.	Pressure .0021 Mm. Nitrogen.	
	Anode 120 Volts.	Anode 235 Volts.
2000	.132	.130
2050	.278	.283
2100	.515	.552
2150	1.07	1.42
2200	2.90	3.90
2250	6.4	8.0
2300	12.9	16.6
2350	>26	>26
a =	1.66×10^9	2.2×10^{10}
b =	68200	73200

These results are plotted (Curves IV., V., Fig. 4) for comparison with the preceding run in a vacuum. It is to be noted that at temperatures up to 2050° the thermionic current, even with such a high pressure of gas, is not as much affected by the anode voltage as it had previously been found to be in a "good" vacuum. The presence of the nitrogen has, however, entirely removed all limitation of the current by space charge at the higher filament temperatures.

Some runs were now made with the filament at fixed temperatures while the anode voltage was varied over a wide range. In most cases

the pressure of nitrogen was kept as nearly constant as possible at .0025 mm.; in some runs, however, the effects produced by a pressure of .0010 mm. were studied.

The data from three runs with the filament at 2100° are given in Fig. 5. The points along Curves I. and II. were obtained with .0025 and .0010 mm. pressure of nitrogen. The nitrogen was then pumped out to a pressure of .00016 mm., and the points along Curve III. were then obtained.

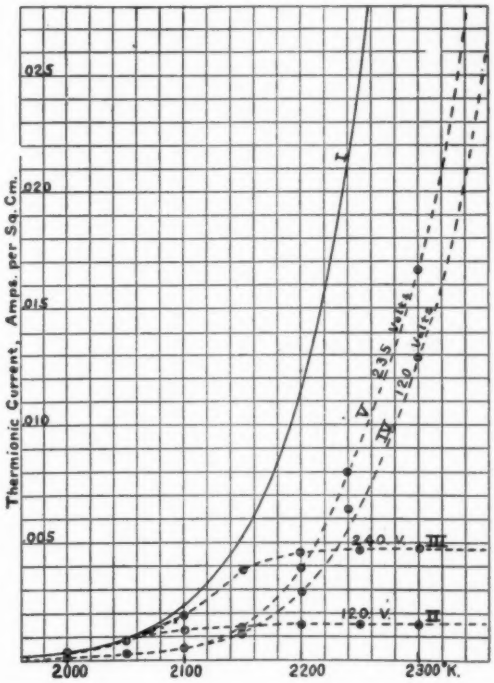


Fig. 4.

These curves help clear up several points that had been left very indefinite by the previous data. At anode potentials below 80 or 90 volts the effect of nitrogen is evidently to increase the thermionic current materially. But above a certain critical potential, which is higher the lower the pressure of nitrogen, the thermionic current decreases as the anode potential is raised. By comparison of the data on these curves with the curves of Fig. 4, it is seen that they are entirely consistent with the latter.

In looking for an explanation of the shape of these curves, it is important to bear in mind that the lower parts of the curves are determined primarily by the space charge. When the thermionic current is plotted

against *temperature*, as in Figs. 1 and 3, the lower part of the curve gives the saturation thermionic current (Richardson), while the upper part gives the part which is limited by the space charge. On the other hand, when we plot the current against the *anode potential*, as in this case, the two parts are interchanged in position; thus the lower part of the curve gives the current as limited by space charge and the upper horizontal part gives the saturation current.

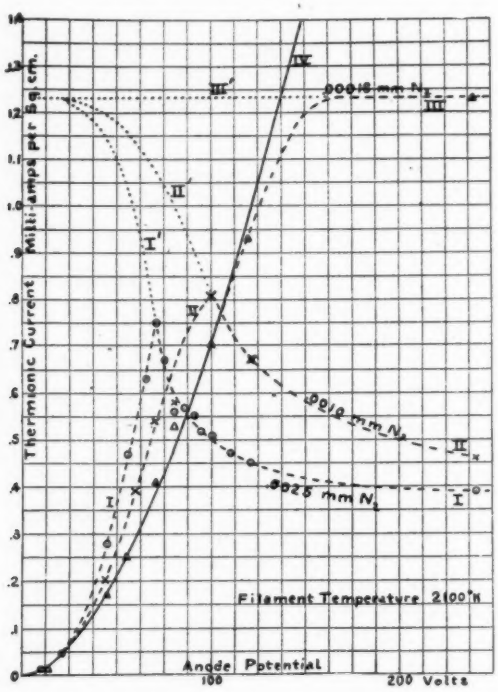


Fig. 5.

The lower part of Curve III., if obtained in a perfect vacuum, should therefore follow equation (11): in other words, the current should increase with $V^{\frac{3}{2}}$. By plotting the first six points of this curve on logarithmic paper, a straight line was obtained, but the slope, instead of giving 3/2 as the exponent of V, gave 1.71. This difference is certainly due to residual gas. Curve IV., Fig. 5, was obtained by continuing the curve

$$i = \text{constant} \times V^{1.71}.$$

The Curve III. separates from IV. above 125 volts because the current gradually reaches saturation for the filament at 2100°.

We are now in a position to discuss the Curves I. and II. At anode potentials below 20 volts the curves seem to coincide fairly well, but

the current rapidly increases at higher potentials. Plotting the first six points of Curve I. on logarithmic paper does not give a straight line, but the exponent of V is found to increase from about 2 to over 6. The cause of this rise in current is probably that positive ions are formed by the collisions of the electrons with nitrogen molecules. The positive ions moving slowly carry only a very minute fraction of the current, yet by their mere presence they materially reduce the space charge and therefore allow a larger current to flow.

If this were the only factor, one would expect with increasing voltage that the current would rise to the normal saturation current and then remain constant until the voltage reaches a point where additional electrons are liberated from the cathode by the impact of positive ions against it. But before this point is reached, some other factor begins to make itself felt. This is evidently a limitation of the current not by space charge, but by some phenomenon which prevents the emission of electrons from the cathode. It is, however, not due to a simple alteration of the properties of the material of the cathode, for its magnitude depends on the anode potential.

The following theory seems to be consistent with all the observed facts and may prove to be the correct explanation of the phenomenon.

Theory of the Effect of Nitrogen on the Thermionic Current.—The writer has shown[1] that nitrogen does not react perceptibly with solid tungsten at any temperature, but does react completely with all the tungsten that evaporates from the filament to form the compound WN_2. The evidence indicated that this compound is unstable at temperatures above 2400°. Now although ordinary nitrogen does not react with solid tungsten to form a compound, it is not improbable that nitrogen ions possessing enormously high kinetic energy as compared with the ordinary molecules, will do so. The compound formed, however, being unstable, does not permanently remain on the surface, but either decomposes or volatilizes. Any such process, however, requires a certain amount of time, so that the molecules would remain on or in the surface during perhaps a perceptible fraction of a second. The higher the temperature of the filament, the shorter the average time that would elapse between the formation of a molecule of the compound and its elimination from the surface.

Let us now apply this theory to the data presented in Fig. 5. At an anode potential below 20 volts, no positive ions are formed, so the surface of the tungsten is not exposed to bombardment. At higher voltages the positive ions are produced in increasing numbers and strike the

[1] Jour. Amer. Chem. Soc., *35*, p. 943 (1913).

cathode with increasing velocity. As a result the surface becomes more or less completely covered by a layer of molecules of the compound. Since as a rule a compound would be expected to emit electrons less freely than a metal, it is not unreasonable to imagine this surface layer as being the cause of the decreased electron emission.

In a perfect vacuum the actual *electron emission* from the tungsten is independent of the anode voltage as indicated in Curve III'., Fig. 5. However, at low anode voltages the space charge causes most of the electrons to return to the filament, so that the actual *current* obtained is as shown in Curve III. On the other hand, in low pressures of nitrogen the actual electron emission decreases as the anode potential increases, as illustrated by the hypothetical Curves I'. and II'. As in the case of the vacuum, however, at low voltages the space charge causes the return of most of the electrons to the cathode, so that the actual curves (I. and II.) show a current which rises rapidly with increasing potentials. When the potential becomes sufficient to prevent the return of any electrons to the cathode, then the current becomes limited solely by the electron emission from the metal. At high voltages, therefore, the current decreases with increased anode potential because of the increasing proportion of the cathode surface covered with the compound.

The theory thus accounts for the shape of the curves in Fig. 5 in a satisfactory way. It also gives a reason for the shape of the curves obtained with nitrogen given in Fig. 4. The effect of nitrogen has invariably been to greatly decrease the saturation current at 240 volts. At low temperatures this effect is much more pronounced than at high. This is indicated by the fact that the introduction of nitrogen (or oxygen) always increases the value of Richardson's constant b from 55,000 up to 80,000 or more. These facts are in complete accord with the theory, for, as has been pointed out, the length of time that the molecules of the compound will remain on the metal would be much less at high temperatures. Therefore, the higher the temperature, the smaller the proportion of the surface covered by molecules of the compound, and the nearer the observed thermionic current approaches the normal saturation current.

Whatever the nature of change in the surface of the tungsten which decreases the electron emission, it is one which does not persist for more than a few seconds after the removal of the nitrogen. In the course of all these experiments, except before ageing the filaments, there were never any effects which could not be immediately duplicated after interchanging the functions of the two electrodes. There is therefore no reason

to call upon any "inexhaustible supply of gas" in the filament to account for any of the phenomena observed.[1]

Effect of Anode Potential at Higher Filament Temperature.—The data on the effect of anode potential obtained with the filament at a higher temperature, 2300° K., is given in Fig. 6. With .0010 mm. of nitrogen, the current rose steadily (Curve I.) until a potential of about 135 volts was reached. With potentials higher than this, the current would rise to a high value, .013 amp. per sq. cm. or more, immediately on lighting the filament, and the discharge was accompanied by a strong purple glow filling the bulb. Suddenly the current fell to .005 amp. per sq. cm. or less, and at the same time the purple glow vanished. Every time that

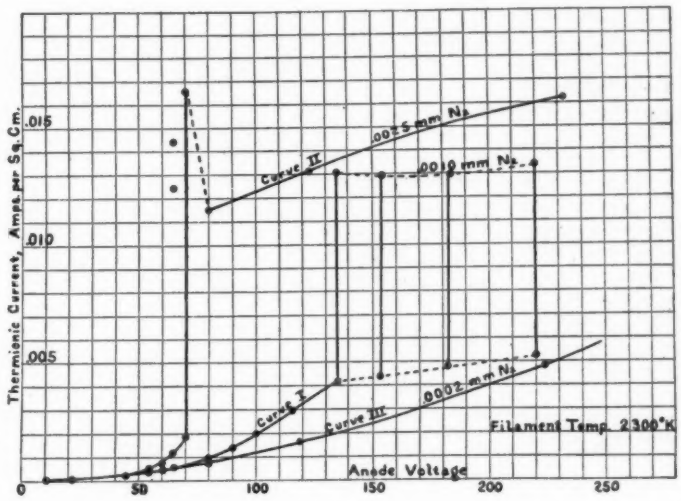


Fig. 6.

this happened the pressure in the system would fall to from about .0012 to .0006 or less, so that fresh nitrogen had to be admitted after each trial.

With a pressure of about 0.0025 mm. of nitrogen (Curve II.) a discontinuity occurred in the current values at an anode potential of 70 volts. Above this, however, the current was again steady. These unstable conditions are probably due to ionization reaching such a value that the bombardment of the cathode by the positive ions gives rise to additional electrons. These in turn cause the formation of fresh positive ions. The effect is thus one which can readily become unstable. It is

[1] The writer feels strongly that the majority of the cases cited in the literature where fine platinum wires, etc., apparently continue to give off gas after prolonged heating, are caused not by gas from the wire, but by water vapor or other gases liberated from the walls (or vapors from stopcock grease or sealing-wax) which are changed chemically by the hot wire or by electrical discharges.

interesting to note, however, that even with this additional electron emission, the current is still less than the *saturation* current in a perfect vacuum, which from Curve I'., Fig. 4, would be about .050 ampere per sq. cm. Undoubtedly at higher pressures and voltages than those used the currents caused by ionization would ultimately greatly exceed the saturation current from the filament.

Curve III. gives the current obtained with a much better vacuum and probably represents very closely the normal current as limited by space charge. The effect of the nitrogen is thus mainly to produce positive ions and neutralize the space charge.

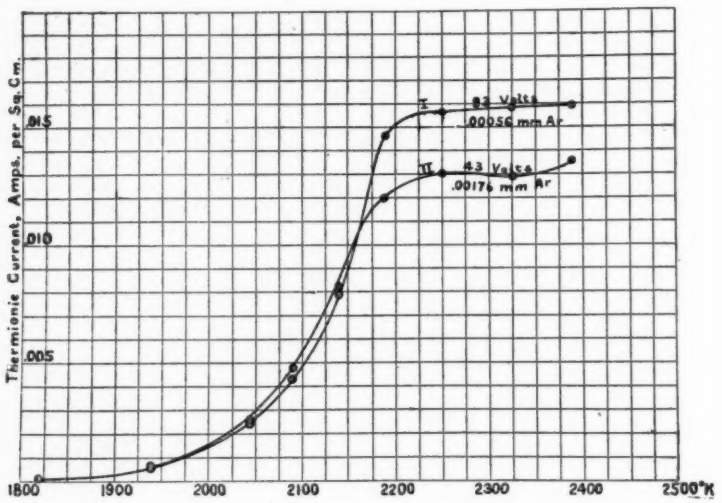


Fig. 7.

Argon.—A series of experiments was made to determine the thermionic current in low pressures of argon. The surprising result was obtained that the saturation currents were in every case (pressures up to .002 mm.) identical with the results previously obtained in the best vacuum. That the argon had the further effect of neutralizing the space charge is shown by the relatively large currents obtained with anode voltages of only 40–100 volts.

In all, about thirty runs were made, and with two exceptions they all gave values of the Richardson constant b between 50,500 and 58,000. The Curves I. and II., Fig. 7, are examples of typical runs. It is seen by comparison with Fig. 3 that the maximum currents obtained are considerably larger than those to be had in vacuum with similar voltages, but these larger currents are due solely to the removal of the limitation imposed by the space charge. At lower temperatures the currents obtained are practically identical with those in vacuum.

Another remarkable fact about the effect of argon on the thermionic current is that considerable admixtures of nitrogen or even oxygen have little or no effect. Thus, while the filament was running at 2190° in argon at .0016 mm. pressure, an amount of nitrogen was let in, which raised the pressure to .0035, yet the current at 240 volts changed only about 5 per cent.

In another case, while the filament was running under similar conditions as in the test with nitrogen, an amount of oxygen was suddenly admitted sufficient to raise the total pressure from 0.0016 to 0.0035 mm. In this case the current was decreased by about 10 per cent. for a few seconds, but rapidly returned within a couple of per cent. of the original value. Upon lowering the temperature to 2045°, the thermionic current was found to be only 7 per cent. of its value in argon, while at 2140° it was 20 per cent. of its original value. If these results are compared with those cited previously on the effect of oxygen on the thermionic current, it will be seen that the argon has enormously weakened the effect produced by oxygen, especially at higher temperatures.

Argon acted remarkably in another respect. The thermionic current in argon caused very marked disintegration of the hot cathode; whereas this effect is entirely absent in a good vacuum with a pure electron current, and only present to a very slight degree in pressures of nitrogen as low as .002 mm. With the argon the filament rapidly increased in resistance by loss of material which deposited on the bulb in the form of black bands, principally behind the *anode*. These bands had more or less the shape of the anode filament and had a white strip down their centers —evidently the shadow cast by the anode. This proves that the tungsten which was sputtered from the cathode was or became *negatively* charged. It is surprising that the thermionic current was identical with that in a high vacuum, notwithstanding this marked disintegration of the cathode. This experiment certainly proves that there is no necessary relation between cathodic disintegration and thermionic current.

These results with argon are strong support for the theory that the positive ions of nitrogen or ordinary molecules of oxygen form unstable compounds with the tungsten which prevent the normal electron emission. Argon not being capable of reacting chemically with the tungsten does not reduce the thermionic currents.

The explanation of the action of argon in preventing oxygen and nitrogen from having their normal effect is probably that the bombardment of the cathode by the positive argon ions, which is undoubtedly (in accordance with Stark's theory) the cause of the sputtering of the cathode, also sputters away any compound formed and thus keeps the

surface of the tungsten clean. At lower temperatures and hence lower currents, the sputtering is less marked and therefore the argon interferes less with the normal action of the oxygen.

EXPERIMENTS WITH PLATES AND CYLINDERS AS ANODES.

In all the experiments mentioned thus far, the anode has been a tungsten filament which has been freed from gas by heating to 2500°. Several experiments, however, were also made with anodes of thin sheet metal, in the form of plates or cylinders. In general, in these experiments, unless very special methods of treating the electrodes are adopted, the evidences of the presence of gas are much more marked than in the experiments with filaments as anodes. A great variety of erratic effects occur, such as gradual changes in the thermionic current, and various kinds of fatigue effects. Some of these effects are particularly pronounced at low temperatures of the filament. A large amount of data has been obtained in studying these effects, and much of it is of such interest that the results will be published in detail in subsequent papers. For the present it will suffice to consider the results of a few runs at various filament temperatures and anode voltages, in a lamp containing a cylindrical anode.

The anode in this experiment consisted of a cylinder of platinum foil, 3.5 cm. diameter and 6 cm. long. Inside of this, about 1 cm. apart, were placed two single loop tungsten filaments of wire .0127 cm. diameter and each 9.9 cm. long. The surface of each was thus 0.40 sq. cm. A cylindrical glass bulb fitted closely about the platinum cylinder.

The platinum cylinder, before placing in the lamp bulb, was ignited for a few minutes over a blast lamp to a white heat and washed with nitric acid, but other than this, purposely not subjected to special treatment.

This lamp was sealed to the same system as before and the same care was used in exhausting it as in the other experiments. That is, after exhausting to 0.001 mm., the bulb was heated to 370° C. for an hour and a half. From the beginning to the end of the experiment the trap directly below the lamp was kept in liquid air.

During the first few days the results were extremely erratic and were characterized especially by lag or fatigue effects. The results showed clearly, however, that these were not due to gas contained in the filament, but were rather caused by gas from the anode liberated by electron bombardment. The quantities of gas liberated, however, were very small, so that even with the Töpler pump no great difficulty was experienced in keeping the pressure continually below .001 mm.

The runs about to be described were made on the tenth day after the

beginning of the experiment. By this time most of the erratic effects had disappeared and the results obtained were beautifully reproducible.

A series of runs was made with the following anode voltages, and in the following order: 240, 124, 30, 50, 70, 90, 70, 50, 30, 20, 110, 124. At each voltage the thermionic currents were measured at temperatures from 1850° to 2350 or 2500°, in steps of 50°. The pressure during all these runs varied within the limits .00007 to .00023 mm. In every case different runs at the same anode voltage gave practically identical results. Furthermore, at temperatures so low that saturation current was obtained, the thermionic currents at different voltages were the same.

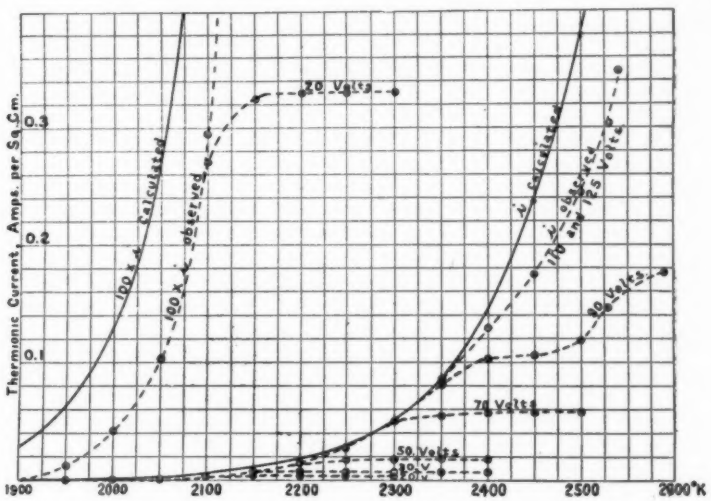


Fig. 8.

The results of these runs are given in Fig. 8. All the experimentally determined points are given, except where the curves run together, and then the points for the curve made at 110 volts are given.

For comparison with these results, the Curve I., of Fig. 3, has been replotted in Fig. 8 (continuous heavy line). This curve gives the results that were obtained under good conditions in a vacuum and in a case in which temperatures were determined in the same manner as in the present experiment.

The upper portion of the curve (not given in Fig. 3) was calculated by Richardson's equation, using the constants

$$a = 34 \times 10^6,$$

$$b = 55{,}500.$$

It will be seen, from Fig. 8, that the currents obtained with the cylin-

drical anode are much larger than any recorded previously in this paper. Thus with 110 volts or more, currents up to 0.350 ampere per sq. cm. (actual current measured was 0.139 amp.) were obtained. But the curves show plainly that at the *same temperature* of the filament, the currents are always less than those obtained under the best vacuum conditions. The shape of the anode reduces the effect of space charge and thus allows much more current to flow with the same voltage than in the previous experiments.

This experiment offers the most convincing evidence possible of the correctness of the general theory of the effects of gas outlined previously.

According to this theory, the effect of certain gases (probably most gases except the inert gases) is to *cut down* the normal electron emission

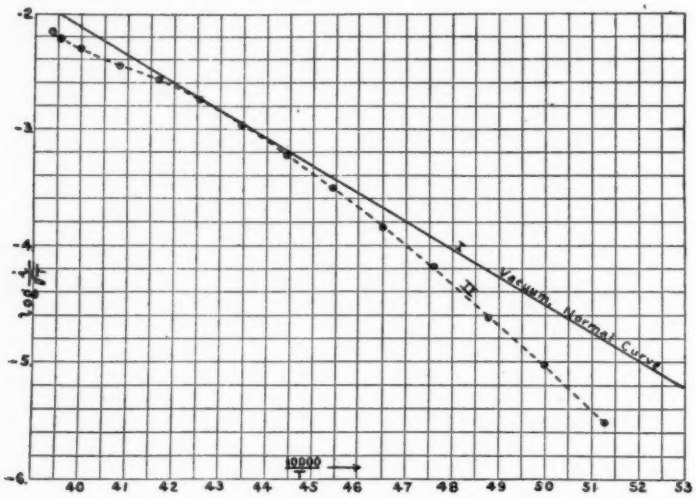


Fig. 9.

from the heated metal, by the formation of an unstable compound on the surface. At higher temperatures the rate of decomposition or evaporation of the compound is greater and hence fewer molecules of the compound remain on the surface. At sufficiently high temperatures the compound should completely disappear and thus allow the electron emission to become normal.

The present experiment is in full accord with this theory. At low temperatures the electron emission (saturation current) is much less than the normal, but at higher temperatures it increases rapidly up to the normal value, but the current *never exceeds the normal current.*

These facts are made much clearer by plotting $\log i/\sqrt{T}$ against $1/T$ (Fig. 9). With these functions as coördinates, the points should lie on a

straight line if the current follows Richardson's equation. Curve I. is the normal vacuum curve shown in Figs. 3 and 8, and Curve II. is that obtained from the experiment with the cylindrical anode at a potential of 110 volts. It is seen that the second line is not straight. The lower part is practically straight, but the upper part *does not cross* the normal vacuum curve, but instead bends over and joins it. The reason that it does not follow it at higher temperatures, is probably that space charge is having some effect, as in the run with 90 volts (see Fig. 8). The *extremely* close coincidence between the observed and calculated curves over the short range of contact is undoubtedly partly accidental.

The fact that the curves obtained at low anode voltages (20–30 volts) coincide at lower temperatures with the curves obtained with high potentials, show in this case that the compound on the surface is not formed from positive ions, but is formed directly by a reaction between the gas and the metal. The gas in this case is probably carbon monoxide or hydrogen, and can easily be supposed to react in this way to form unstable compounds. With nitrogen, on the other hand, the evidence is good that the compound only forms when positive nitrogen ions strike the filament.

The effect of the gas in eliminating the space charge is strikingly shown in this experiment. At higher potentials the thermionic current increases much more rapidly than the three halves power of the voltage. This shows that positive ions are formed which reduce or eliminate the space charge produced by the electrons, yet themselves do not carry a perceptible portion of current.

Some other experiments, to be described in detail in a subsequent paper, have shown, that the bombardment of the cathode even by positive ions of a velocity corresponding to only 110 volts, causes the cathode to emit electrons having a velocity corresponding to a velocity of 6–12 volts. Thus a third filament in a bulb in which a thermionic current is flowing often charges up rapidly to a potential of 10 volts *negative* with respect to the *negative* end of the cathode filament. This observation is entirely in line with previous observations on delta rays and electron emission caused by canal rays.

GENERAL DISCUSSION.

The evidence presented in this paper and the theories that have been advanced are thought to throw a rather new light on the electron emission from incandescent solids in high vacuum.

In the first place, the work indicates that the experimental conditions that have commonly been employed in the investigation of thermionic

currents in vacuo have not been well adapted to eliminate important secondary effects. The proper conditions seem to be:

1. Extremely high vacuum; that is, a pressure below .0001 mm. should be obtained. The presence of certain gases is much more injurious than others. Gases such as oxygen, water vapor, carbon dioxide, and hydrocarbons, which are very active chemically at high temperatures, should be especially avoided. This means that all stopcocks and sealing-wax must be eliminated and all glass parts not to be cooled by liquid air must be heated for at least an hour to 360° or more. Even with the Gaede molecular pump these precautions are necessary.

2. Avoidance of large anodes, except those that have been especially treated by heating in a vacuum to 2000° or have been exposed to powerful electron bombardment in a very high vacuum. Treating the metal by making it an electrode in an ordinary glow discharge, except when the inert gases are used, is about the worst thing that could be done to it. Preferably the anode should consist of tungsten wire which is freed from gas by heating to 2500° for ten minutes. This should be done in the apparatus itself.

3. The relative position and size of the electrodes should be such that space charge does not limit the current to an undesirable degree.

If proper precautions are taken to obtain an extremely high vacuum, and if the anode consists of molybdenum or tungsten and is given a preliminary treatment by exposing to very powerful electron bombardment, it is possible to use cylindrical anodes without obtaining the slightest evidence of positive ionization. For this purpose the anode should be charged to several thousand volts and the filaments raised to such temperatures that 50–200 milliamperes thermionic current are obtained. Under these conditions the anode becomes heated to a bright red or white heat, and the combined effect of the electron bombardment and the high temperature is to free the anode from gas. After such treatment pure electron currents of several tenths of an ampere may be obtained without positive ionization. Dr. Dushman has found that under these conditions the space charge equation (20) holds with a high degree of accuracy.[1] In this way, by using three cylindrical anodes on the guard ring principle, it should be possible to use equation (20) to determine the value of e/m with a degree of precision greater than that obtainable by any other method. Neither the writer nor Dr. Dushman intends to make such precision measurements and therefore we would like to suggest that this method be seriously considered by those who plan to make such determinations.

[1] These results will soon be published by Dr. Dushman.

Failure to observe the conditions given above has, it is feared by the writer, very seriously vitiated most of the quantitative results obtained in the past on thermionic current in a vacuum. It is also undoubtedly the principal cause of the opinion which is so prevalent today that the electron emission from hot solids is a secondary effect, probably usually produced by chemical reactions, which would disappear if a perfect vacuum could be obtained.

The evidence presented in this paper will, it is hoped, counteract these unfortunate tendencies and help place the Richardson theory of electron emission on a firm footing or at least stimulate the critical study of the theory. The thermionic effect is of at least as great intrinsic interest as the photoelectric effect, and should receive as much, if not more, attention on the part of physicists.

Let us now examine more closely some of the experiments which have led to the common knowledge of thermionic currents in vacuo.

With platinum wires extremely variable results have been obtained. H. A. Wilson found that by heating the wire in oxygen or by previously boiling it for 24 hours in nitric acid, the thermionic current would be reduced to the 100,000th part of its original value. This lower value, however, he considers the normal value in a vacuum, and believes the increase observed when hydrogen is admitted to be due to some secondary effect.

The effect of oxygen on the thermionic current from platinum is so strikingly similar to that observed with tungsten that the writer cannot help but feel that the cause in both cases is similar. The writer has found,[1] and will soon publish his results in detail, that when a platinum wire is heated in oxygen at low pressure, the platinum evaporates at the *same rate* as in a vacuum and that the platinum *vapor* combines quantitatively with the oxygen after it leaves the surface of the wire to form the compound PtO_2. This is identically the same type of reaction that has been observed with tungsten and nitrogen. This suggests strongly that oxygen would have a similar effect on the thermionic current from platinum that nitrogen has on tungsten. In other words, the oxygen would cut the thermionic current down to a value *lower* than the normal vacuum current. Hydrogen would reduce the oxide and allow the normal current to flow. Of course it is quite possible, although not probable, that some gases may increase the thermionic current instead of decreasing it.

[1] Jour. Amer. Chem. Soc., *35*, p. 944 (1913).

PRING AND PARKER'S EXPERIMENTS.[1]

The excellent experiments of these investigators have been perhaps the most convincing evidence that the thermionic electron emission is a secondary effect. Let us therefore criticize the experiment in the light of the new theory.

In the first place, carbon is a substance which at high temperatures is particularly active chemically, so that it probably reacts with every gas present in the system. The residual gases may therefore be expected to have a particularly strong action in reducing (or possibly increasing) the thermionic current. Although Pring and Parker have attempted to obtain a high vacuum, and have measured the pressures, yet the best vacuum they claim to have attained, while heating the cathode, is .001 mm. Actually, however, the pressure must have been at least several times this amount, for mercury vapor (.002 mm.) had free access to the apparatus and they used "soft wax" in several places, which gives off large quantities of various vapors, all of which are readily condensible and therefore not indicated by the McLeod gage.

In the second place, the distance between anode and cathode in their experiments varied from 4.8 to 11 cm., so that in a perfect vacuum, with only 330 volts on the anode, they could have obtained only very little current because of the space charge. For example, if we calculate from equation (11) the total current that could be carried at 330 volts between two electrodes 8.0 cm. in area at a distance of 4.8 cm., we obtain only .0048 ampere. Whereas Pring and Parker obtained currents as high as 40 amperes, with only 40 to 60 volts in the beginning; later on, after the carbon had ceased giving off large quantities of gas, the currents fell to as low as .000016, with the temperature of the carbon rod at 2050°.

The reason that the currents in their experiments went down to values so much below that which we have calculated above from the "space charge" equation may possibly be that the electron emission was actually decreased to that low value by the presence of gas. A much more probable explanation suggests itself by referring to the diagram of their apparatus (Fig. 1, Pring and Parker's paper). Apparently they have placed a glass cylinder, *F*, around the anode, in order to protect the walls of the tube from the radiation from the hot anode. In discharges at high pressures this cylinder would have little or no effect on the discharge, but at low pressures, where the free path of the electrons from the cathode becomes commensurate with the distance (apparently about 2 cm.) from the cathode to this cylinder, the effect is very important. At very low pressures these electrons charge up the cylinder to the

[1] Phil. Mag., *23*, 192 (1912).

potential of the anode and therefore practically destroy the potential gradient close to the cathode, where it is especially needed to remove the space charge. The writer has often observed effects of this kind in connection with his work: in fact, in very high vacuum the charging up of the glass sometimes becomes very troublesome. Thus, in some cases, after measuring a thermionic current with 240 volts on the anode, no current at all will be obtained when the anode potential is changed to 120 volts. By touching the bulb with the hand and then with the other hand touching the positive terminal of the direct current supply line, the current instantly starts up again.

In Parker and Pring's experiments, therefore, as the vacuum improved, the potential available for the removal of the space charge decreased very rapidly, and this effect is probably responsible for the extremely small currents obtained by them in some cases.[1]

Lilienfeld's Experiments.[2]

Lilienfeld has concluded from the results of very careful and elaborate experiments in which we took precautions to obtain a particularly high vacuum, that positive ions play an essential rôle in conduction of electricity, even through the highest vacuum. He finds that beyond a certain point these effects are entirely independent of the degree of vacuum. He finds also that the potential gradient is uniform in the space between the electrodes and that the current varies almost exactly proportional to the *square* of the potential gradient. He shows from these results that there is no space charge (except at extremely low currents), but that there must be equal numbers of positive and negative ions in every unit of volume.

Lilienfeld used a Wehnelt cathode as a source of electrons, and anodes of platinum foil, which were kept cold by liquid air while the discharge passed.

These results are so radically different from those that have been described in the present paper, that they call for comment. The effects observed by Lilienfeld are certainly real, and prove that the kind of discharge that he was studying is totally distinct from the pure electron currents that have been obtained with hot tungsten cathodes.

The essential difference in the conditions is undoubtedly the use of the Wehnelt cathode.

[1] In still more recent work Pring (Proc. Roy. Soc., *89*, 344, 1913) again finds the electron emission from carbon to be due entirely to secondary effects. Undoubtedly the large currents that have often been obtained are due to these causes, but some measurements we have made show clearly the existence of a true electron emission. (See Appendix).

[2] Ann. Phys., *32*, 673 (1910).

From some experiments made in this laboratory with Wehnelt cathodes, and judging from the experiments of Child[1] the writer is strongly of the opinion that the Wehnelt cathode is not a primary source of electrons at all, but is simply a cathode which is particularly sensitive to bombardment by positive ions and under the influence of such bombardment emits electrons copiously.

In Lilienfeld's experiments, with the long and crooked path between anode and cathode, the space charge would have prevented a pure electron discharge from taking place. The Wehnelt cathode, however, probably liberates quantities of gas sufficient to furnish the positive ions necessary. It is also possible that Lilienfeld obtained a steady evolution of sufficient gas by the electron bombardment of the anodes which had never been properly freed from gas.

APPENDIX.[2]

Since the foregoing paper was written, a large amount of data on thermionic currents from various metals have been obtained under conditions of still better vacuum. The measurements thus far made are of a preliminary nature, but seem to indicate that the normal thermionic current from tungsten is even larger than that previously given. Much more accurate determinations of the thermionic currents from tungsten, tantalum, molybdenum, platinum and carbon are in progress, and will be published. The results thus far show that with all these substances, the effect of residual gases is always to decrease the thermionic current. Often the current obtained after the best vacuum conditions have been attained is 100–1,000 times as great as that observed when only the usual means of obtaining so-called high vacuum are employed.

The following preliminary results, giving the observed thermionic currents in milliamperes per sq. cm. from various filaments at 2000° K., may be of interest, but should be considered merely as lower limits to the normal electron emission in a perfect vacuum:

Metal.	Thermionic Current at 2000° K. Milliamps. per Sq. Cm.	Richardson's Constant b.
Tungsten	3	55,000
Tantalum	7	50,000
Molybdenum	13	50,000
Platinum	0.6	80,000
Carbon	1.0	32,000

The values of b given in the last column are probably all slightly too high. With platinum it is extremely difficult to get concordant results,

[1] PHYS. REV., *32*, 492 (1911).

[2] Added during correction of proof.

probably because the surface film is fairly stable, even close to the melting-point of the metal. Fredenhagen[1] has recently given reasons for concluding that none of the measurements thus far made of thermionic currents from platinum have really given anything more than secondary effects. He suggests that the presence of an oxide film may seriously affect the results. Our experience has fully confirmed his conclusions.

Summary.

It is shown both theoretically and experimentally that the mutual repulsion of electrons (space charge) in a space devoid of positive ions, limits the current that flows from a hot cathode to a cold anode. For parallel plane electrodes of infinite extent, separated by the distance x, and with a potential difference V between them, the maximum current (per unit area) that can flow if no positive ions are present is

$$i = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{x^2}.$$

For the analogous case of an infinitely long, hot wire, placed concentrically within a cylindrical anode, of radius r, the maximum current per unit length is

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{r\beta^2},$$

where β varies from 0 to 1, according to the diameter of the wire, but for all wires less than 1/20 the diameter of the anode, β is a quantity extremely close to unity.

2. In the presence of gas at pressures above .001 mm., and at voltages above 40 volts, there is usually sufficient production of positive ions to greatly reduce the space charge and thus allow more current to flow than indicated by the above equations.

3. It is shown, contrary to the ordinary opinion, that the general effect of very low pressures of gas is to greatly *reduce* the electron emission from an incandescent metal.

4. This effect is especially marked at low temperatures. In most cases it probably disappears at very high temperatures.

5. The constant b of Richardson's equation

$$i = a\sqrt{T}e^{-\frac{b}{T}}$$

is always increased, in the case of tungsten, by the introduction of oxygen, nitrogen, water vapor, carbon monoxide or dioxide. Argon, however, has no effect on either constant.

[1] Leipziger Berichte, math. phys. Kl., 65, 42, 1913.

6. The normal thermionic current from tungsten in a "*perfect*" vacuum follows Richardson's equation accurately. The constants approximately:

$$a = 34 \times 10^6 \text{ amps. per sq. cm.,}$$

$$b = 55{,}500.$$

7. Preliminary data are given for the electron emission from tantalum, molybdenum, platinum and carbon. With these substances also the effect of gases is to greatly decrease the electron emission.

8. The effect of nitrogen in decreasing the thermionic current from tungsten depends on the voltage of the anode. In many cases less current is obtained with 240 volts than with 120 volts. With oxygen, the effect seems independent of the anode voltage.

9. The following theory seems to account for most of the observed phenomena and is apparently not inconsistent with any:

The effect of gases in changing the saturation current is due to the formation of unstable compounds on the surface of the wire. In the cases observed the presence of the compound decreases the electron emission. It is possible, however, that in some cases it might cause an increase. The extent to which the surface is covered by the compound depends on the rate of formation of the compound and on its rate of removal from the surface. The compound may be *formed* on the surface directly by reaction with the gas (for example, oxygen), or by reacting principally with positive ions which strike the surface (nitrogen). The compound may be *removed* from the surface by decomposition, evaporation, or cathodic sputtering (*i. e.*, being driven off by bombardment of positive ions).

10. The experimental conditions which should be met, in order to most easily study the thermionic currents in high vacuum, are discussed. It is pointed out that failure to observe these conditions is probably the cause of other investigators having found that the thermionic currents tend to decrease with increasing purity of the cathode and progressive improvement of the vacuum.

11. It is concluded that with proper precautions the emission of electrons from an incandescent solid in a very high vacuum (pressures below $.10^{-6}$ mm.) is an important specific property of the substance and is not due to secondary causes.

In conclusion the writer wishes to express his appreciation of the valuable assistance of Mr. S. P. Sweetser, and Mr. William Rogers who have carried out most of the experimental part of this investigation.

RESEARCH LABORATORY,
GENERAL ELECTRIC COMPANY,
SCHENECTADY, N. Y.

THE SENSIBILITY CURVES FOR SELENIUM; A NEW SENSIBILITY-WAVE-LENGTH MAXIMUM AND A NEW PRINCIPLE.

BY F. C. BROWN AND L. P. SIEG.

RECENTLY Pfund[1] found a maximum in selenium at wave-length 690 $\mu\mu$ which disappeared when the intensity of illumination became very faint. This disappearance calls attention to the complexity of the light action in selenium. The present authors were led to believe as a result of a mathematical analysis that the complex behavior might be simplified by using very short periods of exposure to the light, and even that the maxima might disappear for intense illumination also. We have been surprised to find in the Giltay cell a very pronounced maximum at 800 $\mu\mu$, which disappears with small intensity just as the maximum discovered by Pfund in the region of 690 $\mu\mu$ was observed to vanish. And further, not only does this maximum disappear with intense illumination when the selenium is exposed for a short interval of time, but all maxima disappear, such that the remarkable result is obtained that the change of resistance of the particular cell studied is independent of the wave-length of the incident light between 460 and 790 $\mu\mu$. The change of resistance for light in this region is solely a function of the intensity. This last conclusion is important in that it promises us an instrument for measuring energy in the visible spectrum more delicate than the thermopile or bolometer. In this article we propose to restate the conditions under which the maxima appear and to define a method of using the selenium cell for energy comparisons of the various wave-lengths in the visible spectrum.

THEORY.

First we wish to make clear that for intense illumination made up of all visible wave-lengths, we should obtain the simplest conditions by using short exposures. A mathematical analysis has revealed[2] that for the Giltay cell when exposed to approximately white light there are two direct and two reverse changes taking place and only one conducting

[1] PHYS. REV., XXXIV., p. 370, 1912.

[2] See paper by F. C. Brown, PHYS. REV., 33, p. 403, 1911.

element. On p. 408 of the article referred to are given the rates of change and the constituents of the cell under specified conditions. For a short exposure at 18° C. the changes in the conductivity are made up relatively as follows:

$$A \rightarrow B = \alpha_1 A = 11{,}200 \times .054 = 604$$
$$A \leftarrow B = \alpha_2 B = .8 \times 12 = 9.6$$
$$B \rightarrow C = \beta_1 B = .8 \times .9 = 0.7$$
$$B \leftarrow C = \beta_2 C = 3.6 \times .004 = 0.0$$

Thus it appears that we obtain appreciable changes only between the A and B components, and of these the direct change constitutes about 98 per cent. of the total. But for long periods of exposure the amount of each of the four changes above noted approaches equality, as A becomes less, and B and C become greater. The analysis shows therefore that the short exposure gives simple and single changes, while any long exposure gives a most complex and varying summation, because the amounts of A, B and C are continually changing with time. Maxima obtained for long exposure really have very little meaning until we first establish what part of the maximum can be sorted out and attributed to the direct change from A to B.

But aside from what has just been said, short exposures should give a constant change, because for a short interval the amounts of the A, B, and C components are approximately fixed, and since the rates of change are unvarying under given conditions, the sum of $\alpha_1 A - \alpha_2 B - \beta_1 B + \beta_2 C$ should be constant. For any long interval the interchange of the components makes the process very complex.

We therefore decided to map out the sensibility of the selenium for equal energy throughout the spectrum, by exposing the selenium for only a fraction of a second, using sensibility curves for longer exposure merely for comparison.

There is nothing so far in the theory to indicate why short exposures should or should not give sharp maxima. Short exposures however should give simple conditions.

ARRANGEMENT OF APPARATUS AND METHOD OF MEASUREMENT.

To obtain the sensibility curves, the principle laid down by Pfund[1] was followed. The change of resistance for equal energy was measured throughout the visible spectrum. The arrangement of apparatus is shown in Fig. 1. Light from a Nernst filament, N, manufactured by Pye and Co. for their lamp and scale outfit, is focused by the lens L, on the collimating slit S_1 of a constant deviation monochromatic illuminator,

[1] Phil. Mag., Jan., 1904.

manufactured by Spindler and Hoyer. The Nernst glower was maintained at constant intensity by using storage battery for heating current. The bundle of quasi-homogeneous rays was then focused on the slit S_2, and from there was focused by means of the concave mirror M, upon either the thermopile slit or the selenium cell, as desired. The lenses of the monochromatic illuminator were 20 mm., or $f/12.7$ in diameter, and hence with this apparatus, much of the energy is lost. A new illuminator of greater light-gathering power has been obtained and will be used for future work. The slits S_1 and S_2 were kept of equal width, which varied from 0.2 to 1 mm. The length of the slits was one centimeter.

The thermopile was of the Rubens type, but it was of bismuth-silver wires of the improved design of Dr. W. W. Coblentz. It was remarkably

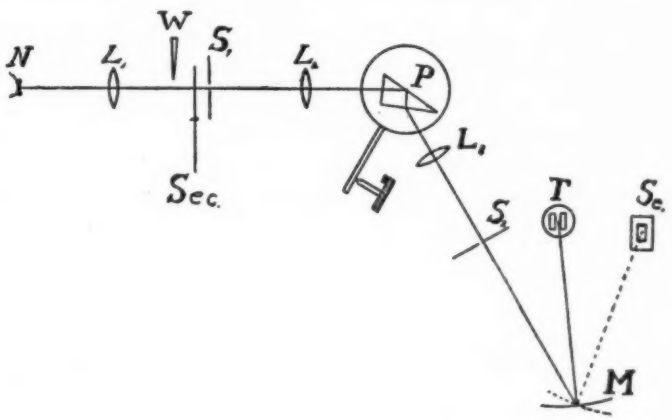


Fig. 1.

free from drift and altogether very satisfactory, as used with a Thomson galvanometer made by Siemens & Halske. The galvanometer had a resistance of 5.4 ohms, and the thermopile had a resistance of 7.4 ohms. This combination when a glass cover was in front of the thermopile junctions gave a deflection of 300 divisions with a candle at a meter. The period was about 5 seconds for this sensibility. By increasing the period the sensibility could have been increased several times, easily to more than 1,000 divisions per candle per meter.[1]

[1] Since the above test was made we have received a standard carbon incandescent lamp from the Bureau of Standards, calibrated for total radiation in a given direction. By means of this standard lamp we found the sensibility of the thermopile to be 9.3×10^{-8} watts/mm. deflection on our scale. It must be remembered that this sensibility was obtained with a glass cover over the thermopile. Had this cover been removed, the sensibility would have been much greater.

A Giltay cell, the one previously studied by one of the authors, was used.[1] It had a resistance of 299,000 ohms in the dark with 4 volts in the circuit, or 270,000 ohms with 20 volts. It was connected in a Wheatstone bridge. For the long exposures a potential of 4 volts was left in the circuit continuously, but for the exposures of a fraction of a second duration the potential was changed to 20 volts. During the experiments the temperature did not vary from 24° by as much as one degree. For the long exposures a Leeds & Northrup high sensibility galvanometer of about 1,000 ohms was used. For the short exposures the method outlined by Brown and Clark[2] was adopted. With this a ballistic galvanometer of 22 seconds period was substituted for the above galvanometer.

We deviated from the procedure outlined by Dr. Pfund in two essentials. An exposure of a fraction of a second was used, and secondly we did not give the cell a special treatment of the nature of preliminary exposure before making each observation. Aside from the advantage of simplifying the conditions, the short exposure has the advantage in that a shorter time is necessary for recovery. We do not believe in the special treatment immediately before making an observation, because such only exaggerates the complexity, and makes it more difficult to define the characteristics of a given sample of selenium. Each distinct preliminary treatment should give a corresponding distinct sensibility curve, providing only that the special treatment varies either in duration or nature of action on the slow rates of change in the selenium.

The intensity of illumination was varied by a rotating sector disc, *Sec*, and an optical wedge, *W*, (Fig. 1) either singly or in combination. It was very easy by this combination to verify the applicability of Talbot's law. However we did not make as extensive a verification as was made by Pfund.

The total area of the selenium exposed was about 4 mm², which was only a little more than a thousandth part of the entire sensitive surface. The fact that only such a small portion of the selenium was exposed was marked only by an apparent decrease of the sensibility of the selenium by a constant value.

We first obtained a family of sensibility curves with varying energy intensity on the selenium using long periods of exposure, 30 sec. In general the energy on the thermopile was adjusted to constant deflection of the galvanometer (20 div.) or to within five per cent. of this value. Then the selenium was exposed to this same bundle of energy. The slit width was 0.2 mm. This width gave a very sharp maximum (see

[1] PHYS. REV., 33, p. 403.
[2] PHYS. REV., 33, p. 53, 1911.

Fig. 2) at 800 $\mu\mu$, a maximum less sharp and much less pronounced at 690 $\mu\mu$, and a broad maximum extending from 540 $\mu\mu$ to 600 $\mu\mu$ (Fig. 2). In obtaining Curve *C* a different practice was resorted to. First the energy from a Nernst glower was measured throughout the spectrum. And then to obtain equal energy on the selenium the calibrated sector disc openings were adjusted in inverse ratio to the energy in the different parts of the spectrum. This method had the advantage of picking out the characteristics of the curve quickly and with a small number of observations, but it required supplementary readings by the other method in some instances in order to obtain higher precision in the relative values of adjacent points. The energy intensity which gave curve *A* was

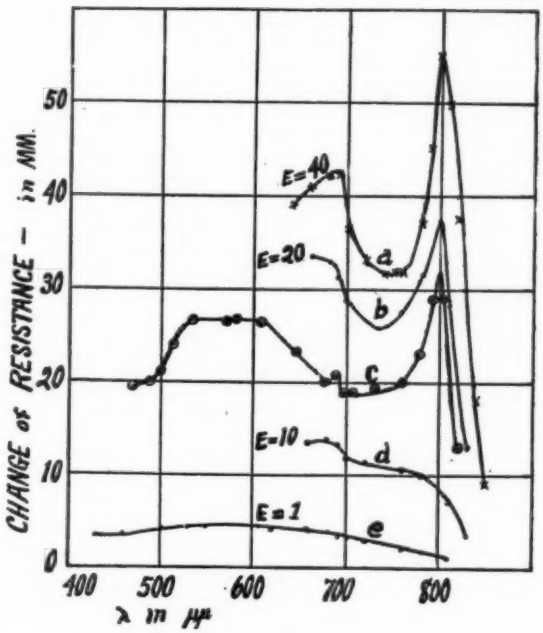


Fig. 2.

about that of a candle at four meters. The intensity of exposure on the selenium was decreased by use of the sector disc by steps, until it was diminished to one fortieth of the above value. The curves are shown in Fig. 2.

The points of interest are first that there is a sharp maximum at 800 $\mu\mu$ which has not hitherto been observed in selenium, and second that faint energy will not bring out this maximum. This last point is very similar to Pfund's observation. The vanishing of the maxima with faint illumination may be explained in terms of the rates of change

existent in selenium. For faint illumination all the rates of change are small, particularly are α_1 and α_2 small in comparison with their values for intense illumination. This simply means that in a 30-second interval with faint illumination there is only time for the A component to be transformed into the B component and of the original B component to be transformed into the C component, and that of the B component for example the excess formed by the light is so small in this time that only the original amount need be considered in the formation of the C component. A long exposure to faint illumination tends to approach the same simplicity that a short exposure to intense illumination accomplishes.

We next tested the effect of varying the time of exposure to intense light referred to in the theory to see if the maximum would tend to vanish. The new duration of exposure was .4 sec. and the slit width was one millimeter. The energy beam was focused on the selenium, so that we obtained a somewhat greater energy intensity than any which gave the curves in Fig. 2. The observations were found to agree with each other very well indeed; five observations were taken for each setting of the illuminator except one. One division on the scale was usually the maximum variation obtained. For the selenium the error was not as great as one per cent. However it was not easy to assure the individual thermopile readings to a greater accuracy than five per cent.

The Curve A (Fig. 3) shows the average of the deflections of the ballistic galvanometer, *i. e.*, the change of resistance, between 500 $\mu\mu$ and 810 $\mu\mu$. It is altogether probable that the single point that is off the curve was off as a result of error due to insufficient number of thermopile readings. By the method that we used it was necessary to diminish the energy in order to make observations beyond 500 $\mu\mu$. By diminishing the energy to 1/20 of the original value the Curve A_2 was obtained. The average of a large number of observations indicated that the independent relationship between wave-length and deflection extended back as far as 460 $\mu\mu$.

The Curves B and C represent the observations for long periods of exposure to the same intensity as above mentioned. The ordinates for Curves B and C are arbitrary and do not correspond to those for Curve A. It is observed that a 60-second exposure (Curve C) makes the maxima and minima slightly more pronounced than a 30-second exposure (Curve B). Perhaps a difference curve between an exposure curve for a very long time and one for a very short time would give a sensibility curve arising solely from the slow changes in the selenium. However this has not been carefully thought out yet. Observations taken after quickly repeated exposures, particularly to longer wave-lengths, tend to smooth

out the maxima. Dr. Pfund has had the kindness to communicate some very interesting and as yet unpublished results by Mr. P. J. Nicholson which are directly in agreement with our result, viz., that the slow rates of change arise from light of the longer wave-lengths. His results show that the form of sensibility curves is markedly altered by varying the wave-length of the preliminary exposure, and that under the continued influence of infra-red radiations (800 $\mu\mu$), the usual fatigue

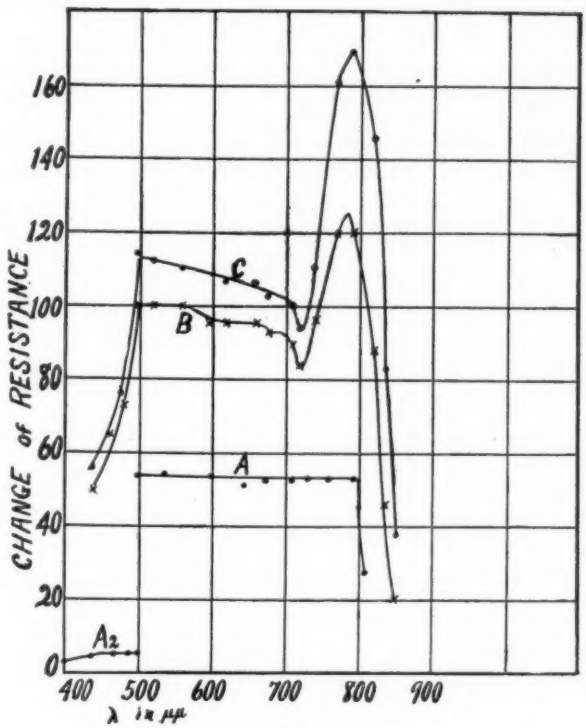


Fig. 3.

A is for 0.4 second exposure; *B* is for 30 seconds exposure; *C* is for 60 seconds exposure.

and lag almost disappear. The fatigue and lag seem to us merely evidences of the slow changes in conductivity.

Having received a more powerful illuminator we are extending our work, to find out the limits in which the change of resistance is independent of the wave-length for short exposure, to establish the law of change of resistance with intensity, and to compare other varieties of selenium and light-sensitive materials.

It is interesting to note how rapidly the curve falls off beyond 800 $\mu\mu$. We are unable to account for a mechanism that would produce a sudden jump of this kind.

The minima as well as the maxima arise from the longer periods of exposure. It may be that minima indicate the normal states for short exposure for particular wave-lengths, which means that spurious maxima arise from slow changes.

SUMMARY.

1. The sensibility curve for a Giltay cell has been determined under varying conditions.

2. In accordance with theory it has been shown that long periods of exposure give varying degrees of complexity, and are responsible for the regions of maximum sensibility.

3. By long periods of exposure a new maximum is obtained at 800 $\mu\mu$.

4. By exposures of a fraction of a second the maxima and minima vanish and between about 460 $\mu\mu$ and 790 $\mu\mu$ the change of resistance is independent of the wave-length.

5. The work thus far accomplished emphasizes the importance of defining simple conditions for obtaining the maxima of such a complex acting agent as selenium.

6. The maxima and also the minima in the Giltay cell studied arise from the slow rates of change.

7. A selenium cell of this type by virtue of the independence of wave-length for short periods of exposure promises to be the most delicate instrument constructed for measuring energy within the range noted.

THE PHYSICAL LABORATORY,
THE UNIVERSITY OF IOWA.

ON THE NATURE OF THE VOLTA EFFECT; A REPLY.

By Fernando Sanford.

IN the July number of this journal Mr. Albert E. Hennings[1] undertakes to show that the results of an experiment as published by the present writer were spurious. Mr. Hennings bases this charge upon the results of some experiments which he claims "reproduce the essential elements of the experiment described by Sanford." In this claim Mr. Hennings is seriously mistaken, as his experiments reproduce none of the essential elements of the experiment described by me.[2] The experiment which Mr. Hennings undertook to reproduce in a more satisfactory manner was performed by lowering an insulated zinc ball into a hollow conductor until it touched the bottom, then withdrawing it and measuring the contact charge taken by the ball from the inside of the hollow conductor or from a disc of another metal resting upon its bottom. The conclusions drawn from the experiment were based upon the assumption that the metal disc inside the hollow conductor was effectually screened from all outside induction. Mr. Hennings criticized the validity of my conclusions because he thought the metal disc and ball were not screened from the inductive effects of a hypothetical charge on the silk thread by which the ball was insulated.

Mr. Hennings's reproduction of the essential elements of this experiment consists in insulating a metal beaker, then lowering an uninsulated steel ball into it by means of a long conductor connected to earth, withdrawing the long conductor and ball and measuring the contact charge left upon the then insulated beaker.

This arrangement of a metallic beaker connected to earth by a long, uninsulated conductor standing up inside it can be called a hollow conductor only by courtesy, and seems to be especially adapted to eliminating all the properties for which hollow conductors have heretofore been used. The outside of a hollow conductor has been defined as the surface most exposed to the induction of surrounding charges. If this definition be adopted, Mr. Hennings has succeeded in introducing the outside of his hollow conductor into the inside of his beaker. It is at least certain that

[1] "Nature of the Volta Effect," Phys. Rev., Ser. II., Vol. I., p. 1.

[2] "On The Nature of the Volta Effect," Phys. Rev., XXXV., 484 (1912).

no experiments in which the shielding properties of a hollow conductor were involved could be performed with such a device as the one invented by Mr. Hennings.

The remainder of Mr. Hennings's paper contains nothing touching in any way upon the validity of the conclusions drawn from my experiment. In fact, he finally comes to the same conclusion as to the nature of the Volta effect that is stated at the end of my paper. I state as a result of what I conceive to be the teachings of my experiment that "Apparently the Volta effect is not due to any electrolytic action between the opposed metals, but different metals when in contact with the earth or with the inside of the same hollow conductor may be at different potentials relative to each other." Mr. Hennings says, "The surfaces of conductors which have been discharged to earth act just as though they were definitely and characteristically charged."

STANFORD UNIVERSITY,
September 12, 1913

THE MAGNETIC SUSCEPTIBILITY OF GASES.[1]

BY W. P. ROOP.

1. The explanation of the magnetic properties of substances in terms of electronic motions is the objective point of the physical theory of magnetic phenomena. Recent work has been done in developing a theory of ferro-magnetic phenomena by Weiss and in investigating the magnetic properties of organic compounds by Pascal. In each of these cases, however, the results have been useful principally as determining susceptibility as a function of structural relations rather than as a fundamental property of matter. On the other hand, the theory of Langevin and the magneton hypothesis of Weiss,[2] supported by work at low temperatures in the Leiden laboratory, look toward a more general theory of magnetism, so that magnetic phenomena may be expected eventually to occupy a place in the *electro-magnetisches Weltbild* of Abraham.

It is unfortunate, however, that experimental work has been of necessity almost entirely limited to investigations of the magnetic properties of solids, liquids, and solutions. For it is only in gases that the molecule is sufficiently free from the disturbing influences of its neighbors so that a direct study of molecular properties, as distinguished from structural properties, becomes possible.

2. The study of the magnetic properties of gases is difficult on account of the extreme smallness of the quantities to be measured. This difficulty becomes apparent in the large differences between results obtained by different observers. Oxygen is the only gas whose susceptibility has been measured with sufficient accuracy to justify a comparison of results. Data are also available for air and NO, but the behavior of these is due to the oxygen content. With other gases, there is no agreement, even as to sign. A partial summary of values for the susceptibility of oxygen is given on the following page.

3. Before systematic study of the magnetic properties of gases can be expected to yield valid results, a method must be devised which shall be

[1] A preliminary report of work conducted under a grant from the Rumford fund of the American Academy of Arts and Sciences.

[2] For a summary of the work of Langevin and Weiss, with references to the papers of the others, see Phys. Ztschrft., 12, 935, 1911.

Observer.	Mean Value.	Mean Error.	Reference.
Quincke....	$.156 \times 10^{-6}$	4.5 per cent.	Ann. d. Ph., 34, 401, 1888.
DuBois.....	.117	.....	Ann. d. Ph., 35, 137, 1888.
Hennig.....	.120	1.6 per cent.	Ann. d. Ph., 50, 485, 1893.
Curie.....	.167	3.5 per cent.	Ann. Ch. Ph., 5, 289, 1895.
Roop.....	.127	5 per cent.	Phys. Ztschrft., 12, 48, 1911.
Piccard.....	.1407	0.1 per cent.	Arch. des Sciences, 35, 480, 1913.

sensitive enough to be used with other gases than oxygen, and which shall give consistent results with oxygen. A suggestion is given by Drude.[1] A manometer consisting of a closed tube containing two fluids (see Fig. 1) becomes very sensitive if the fluids have a small density difference. For ordinary purposes, such a manometer could not be used, since there would be no way of connecting it with the pressure to be measured. But if one of the bounding surfaces be placed in a magnetic field, the surface is displaced into a new equilibrium position such that the hydrostatic pressure due to the displacement is balanced by the pressure due to the displacement is balanced by the pressure due to the magnetic field. The pressure on the bounding surfaces tending to restore them to their equilibrium positions, for a displacement d, is $dg(\rho - \rho_0)$, where ρ and ρ_0 are the respective densities of the fluids. Since there are two such surfaces, each of which is displaced by the same amount, the total pressure tending to restore equilibrium is $2dg(\rho - \rho_0)$. The magnetic pressure tending to disturb the hydrostatic equilibrium is $(\kappa - \kappa_0)/2 \cdot H^2$, where κ and κ_0 are the respective susceptibilities of the two fluids. Equating these pressures, and solving,

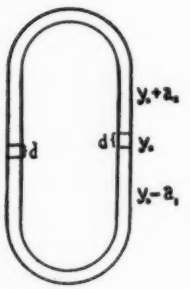


Fig. 1.

$$\kappa - \kappa_0 = \frac{4dg(\rho - \rho_0)}{H^2}.$$

In case the magnetic field intensity H at the other bounding surface is not negligible, this becomes

$$\kappa - \kappa_0 = \frac{4dg(\rho - \rho_0)}{H^2 - H_0^2}.$$

4. Now at the boundary between two gases, there is, of course, no sharp discontinuity. The suggestion of Drude, that a film of liquid be used to separate the gases, seems impracticable. It is possible, however, to carry out the experiment in such a way that the gases only remain in contact with each other for such a short time that diffusion introduces no serious errors.

[1] Physik des Aethers, 1st ed., p. 148.

Consider the effect of diffusion on a boundary initially sharp. In a straight tube, of uniform bore, the diffusion will be symmetrical, so that the section of the gas column originally constituting the boundary remains the section at which the concentrations of the two gases are equal. In what follows we will designate this section as the boundary. On one side the concentration of one gas, and on the other side the concentration of the other gas, will drop off more or less gradually to zero. Let Y be the coördinate parallel to the axis of the tube. Suppose that the diffusion at a given time t has made the mixture of the gases appreciable to a distance a_1 on one side and a_2 on the other side of the boundary at y_0. The density and susceptibility will vary continuously from $y = y_0 - a_1$ to $y = y_0 + a_2$.

On account of the symmetry of the manometer the hydrostatic force caused by the bodily displacement of both gases, together with the region within which diffusion has occurred, up d cm. on one side, and down the same distance on the other, will be the same as if the boundaries were true discontinuities, provided that the diffusion results in the same distribution of gas on one side as on the other, and does not extend beyond the straight parts of the tube.

As regards the magnetic forces, consider the region between $y_0 - a_1$ and $y_0 + a_2$ to be filled with layers of gas mixture of uniform composition enclosed between cross-sections of the tube at intervals of Δy, differing from each other in composition and susceptibility by differential increments. Denote the concentration of one of the gases at point y by c_y. That of the other is then $1 - c_y$. If susceptibility is an additive function in mixtures, the susceptibility of the mixture at y is $\kappa \cdot c_y + \kappa_0(1 - c_y)$. The susceptibility difference between two neighboring layers is therefore $(\kappa - \kappa_0)\Delta c_y$. The magnetic pressure now becomes

$$\frac{\kappa - \kappa_0}{2} \int_{y_0 - a_1}^{y_0 + a_2} H^2 \cdot \frac{dc_y}{dy} dy.$$

Or, if the limits of integration lie within the region over which H has a sensibly uniform value, we have

$$\frac{\kappa - \kappa_0}{2} H^2 \int_{y_0 - a_1}^{y_0 + a_2} \frac{dc_y}{dy} dy.$$

Since the integral gives the concentration difference between the points $y + a_2$ and $y - a_1$, which is unity, the expression for magnetic pressure reduces to that previously given. The conditions, therefore, under which the simple expression for susceptibility is unchanged by diffusion are these:

(1) Diffusion same on two sides of manometer.
(2) Diffusion limited to straight part of tubes.
(3) Diffusion limited to uniform part of field.
(4) Susceptibility of mixtures additive.

5. Of these conditions, (3) is the most questionable. We may determine approximately the extent to which it is met in the following way. Consider the diffusion in a closed tube of bore negligible relative to the dimensions of the manometer. In such a tube it seems justifiable to assume that diffusion proceeds in such a way as not to disturb the uniformity of concentration in any right section of the tube, so that the concentration gradient remains everywhere parallel to the axis of the tube. Let s be the coördinate measured along this axis. The diffusion proceeds subject to the condition

$$\frac{\partial c}{\partial t} = k\frac{\partial^2 c}{\partial s^2},$$

c being concentration of one of the gases, and k the diffusion constant.

Suppose the tube to be half filled with each of two different gases in such a way that the two boundaries separating the two gases are initially sharp. Consider the origin of the coördinate s to be located half-way between the two boundaries. The initial distribution may then be described as follows:

When $t = 0$,

$$c = f_0(s) = 0 \quad \text{where} \quad -l < s < -\frac{l}{2},$$

$$= 1 \quad \text{where} \quad -\frac{l}{2} < s < +\frac{l}{2},$$

$$= 0 \quad \text{where} \quad +\frac{l}{2} < s < +l.$$

Here $2l$ is the entire length of the manometer tube, measured along its axis. Further, for all values of t, at the boundaries, where

$$s = \pm\frac{l}{2}, \quad c = \frac{1}{2}.$$

The Fourier series[1]

$$c = q + \Sigma p_n e^{-k\frac{\pi^2 n^2}{l^2}t} \cos\frac{n\pi}{l}s$$

satisfies all conditions if

$$q = \frac{1}{2}$$

[1] Cf. H. A. Lorentz, Differential- u. Integralrechnung.

and

$$p_n = \frac{1}{l}\int_{-l}^{+l} f_0(s)\cos\frac{n\pi}{l}\,sds$$

$$= (-1)^{\frac{n-1}{2}}\cdot\frac{2}{n\pi} \quad \text{when } n \text{ is odd,}$$

or

$$= 0 \quad \text{when } n \text{ is even.}$$

Since the conditions named, viz., the boundary conditions, the initial conditions, and the condition expressed by the differential equation, determine physically the progress of the diffusion, and since the function represented by the Fourier series satisfies all these conditions, this function must give the true relation existing between the concentration, time, and distribution along coördinate s. Thus we may determine the extent to which diffusion has caused a failure to meet condition (3) at any time t.

6. The method has been tested by the use of a simple apparatus of the form shown in the diagram. The essential part of the apparatus, the gas manometer, is contained between the two three-way cocks, A and B. One arm of the manometer is placed between the poles of a Weiss electro-magnet,[1] with 10 cm. cores. The other arm is at a distance of 3 cm. from the edge of the cylindrical pole-pieces. One side of the manometer is filled with air, the other with CO_2. On turning the cocks A and B so as to connect the two sides of the manometer with each other, the heavier gas settles and fills each side of the manometer in the lower half only, while the upper half of each side is occupied by the lighter gas. If now this process is repeated with the magnet acting on the gases on one side, a different position of equilibrium is reached. The distance between these two equilibrium positions is d. It is determined by forcing the gas out of each side separately into a gas burette by lifting the mercury reservoir, and measuring the volume of air, after having absorbed the CO_2 in the KOH solution with which the burette is filled and operated. The difference between the volume of unabsorbed gas obtained without the field and that obtained with it,

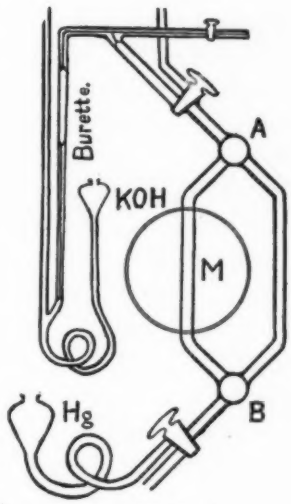


Fig. 2.

[1] A solenoid cannot be used, both on account of temperature disturbances, and because a manometer of excessively large cross-section would be necessary.

divided by the cross section of the manometer tube, gives d. To calculate d, however, it is only necessary to observe the difference in the burette readings in the two cases, and divide by the ratio of the cross-sectional areas of manometer and burette tubes.

7. The total length $2l$ of the manometer was 50 cm. The internal diameter of the manometer tubes was about 4.5 mm., that of the bore of the cocks being 3 mm. The ratio of cross-sectional areas of manometer and burette tubes was found by mercury weighings to be 11.3. It was found to require about 7 seconds after opening the cocks for the boundaries to reach their equilibrium positions. One cock was in each case opened for that length of time, the other, however, was necessarily open a little longer.

The field was determined by means of a bismuth spiral, using the calibration curve furnished by the makers and correcting for the difference (4°) between the temperature of the calibration and that at which the measurements were made. The current necessary was only 2 amperes (capacity of the magnet 20), and the corrected field intensity was 6,220 gausses. The intensity at the other manometer arm, H_0, was 750 gausses. Whence $H^2 - H_0^2 = 38.2 \times 10^6$.

The mean of six observations of burette reading difference is 4.8 cm., whence $d = .425$ cm. This figure leads to the value of 0.030×10^{-6} for the susceptibility difference between air and CO_2, and to this corresponds a value for the susceptibility of oxygen of 0.144×10^{-6}, that of CO_2 being negligibly small.

By substituting the numerical values for the diffusion constant (0.142 C.G.S.) and the dimensions of the apparatus in the equation obtained in paragraph 5, we find that at the end of 7 seconds the air at a distance of 5 cm. from the boundary contains 7 per cent. of CO_2. Doubtless the diffusion somewhat exceeds the calculated amount, on account of the motion of the boundaries from the cocks to their equilibrium positions. Nevertheless the error due to neglecting diffusion altogether must be small, as the result is close to the average of previously obtained values.

SUMMARY.

A new method for determining gas susceptibility is developed which far exceeds previous methods in sensitiveness.

An illustrative set of data taken with air and CO_2 leads to the value for oxygen of

$$\kappa = 0.144 \times 10^{-6}.$$

CORNELL UNIVERSITY,
July, 1913.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

CONDITIONS INVOLVING A DECREASE OF PRIMARY CURRENT WITH INCREASING SECONDARY CURRENT.[1]

BY F. J. ROGERS.

UNDER all ordinary conditions prevailing in practice an increase of the secondary current in a transformer or induction coil is accompanied by an increase in the primary current. Recently the writer accidentally stumbled upon conditions in which the reverse is true.

A purely experimental investigation showed that the conditions favoring this surprising result were as follows: (1) Small mass of copper in the secondary circuit. (2) High resistance in the primary circuit. (3) Low permeability of the magnetic circuit. When these conditions prevailed in sufficient degree, the secondary could be short-circuited causing a powerful secondary current but accompanied by a *decrease* of the primary current.

By the well-known methods of alternating currents an equation was derived representing the primary current in terms of the impressed E.M.F., the frequency, and the resistances and inductances of the primary and secondary circuits. This was done in the following manner:

Assuming that the impressed E.M.F. in the primary circuit is $E \cos \omega t$, the E.M.F. equations for the two circuits are

$$E \cos \omega t = L_1 \frac{di_1}{dt} + R_1 i_1 - M \frac{di_2}{dt},$$

$$O = L_2 \frac{di_2}{dt} + R_2 i_2 - M \frac{di_1}{dt}.$$

Eliminating the secondary current between these two differential equations and assuming that the primary current is $i = I \cos (\omega t - \theta)$ gives a single equation. This equation can be broken up into two by expanding $\cos (\omega t - \theta)$, collecting the coefficients of $\sin \omega t$ and $\cos \omega t$, and equating each of these coefficients to zero. θ may be eliminated between these two equations thus giving the desired result. If reactances be substituted instead of inductances

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 18, 1913.

the equation thus desired, when expressed in its simplest form, becomes:

$$I = \frac{E\sqrt{R_2^2 + x_2^2}}{\sqrt{(R_1x_1 + R_2x_2)^2 + [R_1R_2 - (x_1x_2 - x_{12}^2)]^2}}.$$

I is the primary current and the other symbols have their usual signification, except x_{12} which stands for $2\pi nM$ and may be called *mutual reactance*. When the resistance of the secondary is infinite the above equation reduces to

$$I' = \frac{E}{\sqrt{R_1^2 + x_1^2}}.$$

Multiplying both terms of the fraction by $\sqrt{R_2^2 + x_2^2}$ and simplifying by introducing impedences, our two equations become

$$I = \frac{Ez_2}{\sqrt{(z_1z_2)^2 + x_{12}^2(x_{12}^2 + 2R_1R_2 - 2x_1x_2)}};$$

$$I' = \frac{Ez_2}{\sqrt{(z_1z_2)^2}}.$$

Now it is obvious that the current I for a short circuit of the secondary will be less than I' if

$$x_{12}^2 + 2R_1R_2 - 2x_1x_2 > 0.$$

In order to verify the formula experimentally a coil was constructed with a primary winding of 1,600 turns of No. 16 and a secondary winding of 200 turns

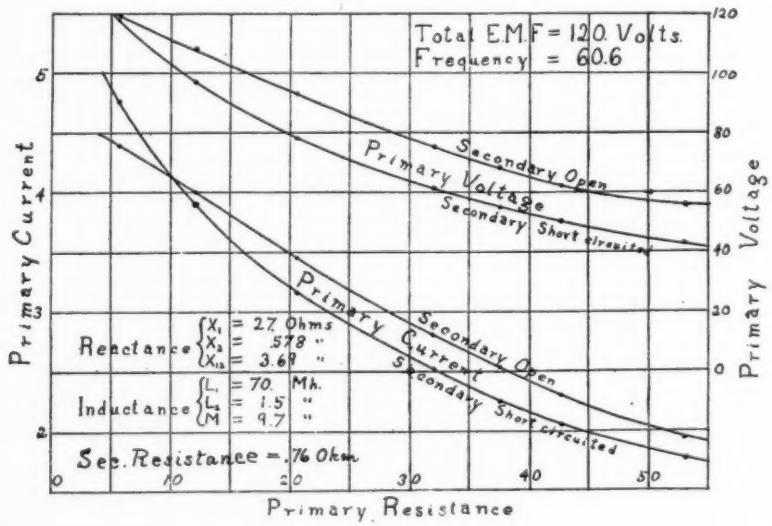


Fig. 1.

of the same wire. All the constants of this coil were carefully measured. Then a rheostat with known resistances was connected in series with the primary and the primary current was measured both for the secondary open and short-

circuited. These currents are plotted against the primary resistances in Fig. 1. With the aid of the constants of the coil (also given in the plot) the primary current was computed for each resistance used, according to the equation derived above. In all cases the difference between observed and computed results were within the errors of observation.

After this work had been entirely completed Dr. Bedell kindly called my attention to a paper by E. C. Rimington, Phil. Mag., Vol. 37, p. 394, in which a theoretical treatment of the air core transformer led to a formula equivalent to the one derived above. In a later paper by Bedell, Phil. Mag., Vol. 42, p. 300, a graphical method for studying the increase and decrease of primary impedance when secondary is closed is indicated.

RELATIVITY THEORY; GENERAL DYNAMICAL PRINCIPLES.[1]

BY RICHARD C. TOLMAN.

THE Einstein theory of relativity has necessitated a revision of the classical Newtonian mechanics. Some of the consequences have already been presented[2] of a system of mechanics which is based on Newton's three laws of motion,[3] the principle of the conservation of mass, and the Einstein transformation equations for coördinate systems in relative motion. In the article of which this presents an abstract, the writer has derived for a system of particles the important principles of the conservation of momentum and of the conservation of moment of momentum. A further principle has been derived corresponding to that of least action which applies in ordinary mechanics, and this leads to generalized equations of motion in the Lagrangian and Hamiltonian (canonical) forms. We find, however, that the Lagrangian function is *not* to be taken as equal to the difference between the kinetic and potential energies of the system as in the classical mechanics, and the generalized momenta used in the modified Hamiltonian equations are *not* to be defined as the partial differential of the kinetic energy with respect to the generalized velocities as in the older mechanics. In non-Newtonian mechanics the Lagrangian function becomes $L = T - U$, where U is the potential energy of the system and the function $T = \Sigma m_0 c^2(1 - \sqrt{1 - q^2/c^2})$, where m_0 is the mass of a particle at rest, q its velocity, c the velocity of light, and the summation Σ extends over all the particles of the system. The generalized momenta ψ_1, ψ_2, etc., to be used in the Hamiltonian equation of motion are defined in non-Newtonian mechanics by the equations $\psi_1 = \partial T/\partial \dot{\phi}_1$, $\psi_2 = \partial T/\partial \dot{\phi}_2$, etc., where $\dot{\phi}_1$, $\dot{\phi}_2$, etc., are the generalized velocities.

It is hoped that this presentation of the principle of least action and its

[1] Abstract presented at the New York meeting of the Physical Society, October 18, 1913.

[2] Lewis and Tolman, Phil. Mag., XVII., p. 510 (1909); Tolman, Phil. Mag., XXI., p. 296 (1911); XXII., p. 458 (1911); XXIII., p. 375 (1912); XXV., p. 150 (1913).

[3] In interpreting the laws of motion we must define force in Newton's original form as equal to the rate of change of momentum instead of in the later form as mass times acceleration, since the two definitions are not identical when the mass changes with the velocity as it does according to the theory of relativity.

consequences, in the modified form necessitated by the principle of relativity, will assist in that careful scrutiny which now has to be given to all the results of the older classical mechanics. In the present article the use of the generalized equations has been illustrated by the derivation of a principle corresponding to that of vis-viva in ordinary mechanics. In a following article the ideas here developed will be used in a consideration of the important problem of the equi-partition of energy.

This derivation of the principle of least action from the laws of motion is also of particular interest, since writers on relativity[1] have made considerable use of the principle in the fields of pure dynamics, electromagnetics, and thermodynamics, without presenting any derivation in the only field—that of pure dynamics—where such can be obtained.

RELATIVITY THEORY; THE EQUIPARTITION LAW IN A SYSTEM OF PARTICLES.[2]

BY RICHARD C. TOLMAN.

THE principle of relativity necessitates a revision of the kinetic theory of gases. For an ideal gas containing monatomic molecules, all of which have the *same mass*, a modified form of the Maxwell distribution law for the momenta of the molecules has already been derived by Jüttner.[3] In the article, of which this presents an abstract, the writer has considered systems containing particles of *different masses*, and derived also for this case a law for the distribution of momenta. From this distribution law it is shown that the average value of $m_0v^2/\sqrt{1-v^2}$ *is the same for particles of all different masses.*[4]

This equipartition of $(m_0v^2/\sqrt{1-v^2})_{av.}$ is found true not only for a mixture of particles of different masses, but also for systems of particles which are separated by a partition that allows transfer of energy. Hence the equality of the average values of this quantity becomes the relativity condition for thermal equilibrium. Furthermore, it is shown that $(m_0v^2/\sqrt{1-v^2})_{av.}$ is proportional to the absolute temperature as measured on the thermodynamic scale, and hence we see that in all such considerations this new quantity satisfies the same relations as the vis-viva m_0v^2 in Newtonian mechanics, and indeed reduces to that quantity when the velocities are small compared with that of light.

We note immediately, however, that the quantity $m_0v^2/\sqrt{1-v^2}$ is neither the relativity expression for the total energy of a particle $m_0\sqrt{1-v^2}$ nor for the kinetic energy $(m_0/\sqrt{1-v^2}) - m_0)$ and hence *in relativity mechanics there can be no possibility of an exact equipartition of energy.* Finally, the writer presents a partial consideration of the actual partition of energy attained at equilibrium.

[1] Planck, Ann. d. Physik, XXVI., p. 1 (1908); Herglotz, Ann. d. Physik, XXXVI., p. 493 (1911); de Wisniewski, Ann. d. Physik, XL., p. 668 (1913).

[2] Abstract presented at the New York meeting of the Physical Society, October 18, 1913.

[3] Jüttner, Ann. d. Physik, XXXIV., 856 (1911).

[4] v is the ratio of the velocity of the particle to the velocity of light.

LIST OF MEMBERS OF THE AMERICAN PHYSICAL SOCIETY

FOREIGN HONORARY MEMBERS.

SVANTE ARRHENIUS. (25) Stockholm, Sweden.

V. F. K. BJERKNES. (31) Geophysikalisches Institut, Nurnberger str. 57, Leipzig, Germany.

H. A. LORENTZ. Haarlem, Holland. Lylweg 76.

MAX PLANCK. (47) Berlin, Germany. Wagenheim str. 21, Grunewald.

E. RUTHERFORD. (4) Univ. of Manchester, 17 Wilmslow Rd., Withington, Manchester, England.

EMIL WIECHERT. (33) Goettingen, Germany.

REGULAR MEMBERS.

ABBE, CLEVELAND. (1) Professor of Meteorology, U. S. Weather Bureau, Washington, D. C.

ADAMS, COMFORT A. (61) Professor of Electrical Engineering and Consulting Engineer, Harvard University, Pierce Hall, Cambridge, Mass.

ADAMS, E. P. (22) Professor of Physics, Princeton University, Princeton, New Jersey.

AGNEW, P. G. (48) Associate Physicist, Bureau of Standards, Washington, D. C.

ALLEN, FRANK. (24) Professor of Physics, University of Manitoba, Winnipeg, Canada.

ALLEN, SAMUEL JAMES MCINTOSH. (37) Assistant Professor of Physics, University of Cincinnati, Cincinnati, Ohio.

ALMY, FRANK FAYETTE. (24) Professor of Physics, Grinnell College; 436 East St., Grinnell, Iowa.

ALMY, JOHN EDWIN. (20) Professor of Experimental Physics, University of Nebraska; Station A, Lincoln, Neb.

AMES, JOSEPH S. (1) Professor of Physics, Director of Physical Laboratory, Johns Hopkins University, Baltimore, Md.

ARNOLD, H. D. (28) 463 West St., New York City.

AUSTIN, LOUIS WINSLOW. (4) Expert in charge, U. S. Naval Radio-Telegraphic Laboratory; Bureau of Standards, Washington, D. C.

BAKER, WILL C. (37) Assistant Professor of Physics, School of Mining, Queen's University, Kingston, Ont., Canada; 110 Victoria St.

BANCROFT, WILDER D. (1) Professor of Physical Chemistry, Cornell University; 7 East Ave., Ithaca, N. Y.

BARKER, H. C. (67) Univ. of Pennsylvania, Randal-Morgan Lab. of Physics, Philadelphia, Pa.

BARNES, HOWARD T. (14) Macdonald Professor of Physics, McGill University, Montreal, Canada.

BARNES, JAMES. (27) Bryn Mawr College, Bryn Mawr, Pa.

BARNETT, S. J. (20) Professor of Physics, Ohio State University, Columbus, Ohio.

BARUS, CARL. (1) Professor of Physics, Dean Graduate Dept., Brown University, Providence, R. I.

BATES, FRED J. (23) Bureau of Standards, Washington, D. C.

BAUER, L. A. (4) Director, Department of Terrestrial Magnetism, Carnegie Institution of Washington; The Ontario, Washington, D. C.

BEACH, FREDERICK E. (1) Assistant Professor of Physics, Yale University, New Haven, Conn.

BECKER, GEORGE F. (30) U. S. Geological Survey, Washington, D. C.

BEDELL, FREDERICK. (1) Professor of Applied Electricity, Cornell University, Ithaca, N. Y.

BENTON, J. R. (13) Professor of Physics and Electrical Engineering, University of Florida, Gainesville, Fla.

BISHOP, F. L. (33) Univ. of Pittsburgh, 12 Grant Blvd., Pittsburgh, Pa.

BISSING, WM. F. (20) 2 Rector St., New York City.

BLACKWELL, HOWARD L. (18) Fellow for Research in Physics, Harvard University; 4 Riedesel Ave., Cambridge, Mass.

BLAIR, WM. R. (42) Research Director, U. S. Weather Bureau, Mount Weather Observatory, Bluemont, Va.

BLAKE, FREDERIC C. (22) Professor of Physics, Ohio State University, Columbus, Ohio; 350 Iuka Ave.

BLAKER, ERNEST. (20) Assistant Professor of Physics, Cornell University; 402 Oak Ave., Ithaca, N. Y.

BLISS, WILLIAM J. A. (2) Collegiate Professor of Physics, Johns Hopkins University, Baltimore, Md.

BOLTWOOD, BERTRAM B. (30) Professor of Radio-Chemistry, Sloane Laboratory, Yale University, New Haven, Conn.

BOYLE, ROBERT WILLIAM. (46) University of Alberta, Edmonton, S. Alberta, Canada.

BOYNTON, W. P. (28) Professor of Physics, University of Oregon; 135 E. 11th St., Eugene, Oregon.

BRACKETT, CYRUS F. (2) Professor of Physics (Emeritus), Princeton University, Princeton, N. J.

BRIDGMAN, P. W. (31) Instr. in Physics, Harvard Univ., Cambridge, Mass.

BRIGGS, LYMAN J. (4) Physicist, Bureau of Plant Industry; 3451 Mt. Pleasant St., Washington, D. C.

BRONSON, HOWARD L. (31) Professor of Physics, Dalhousie University; 45 Seymour St., Halifax, Nova Scotia.

BROOKS, H. B. (66) Bureau of Standards, Washington, D. C.

BROWN, F. C. (31) Assistant Professor of Physics, University of Iowa; 220 Reynolds Ave., Iowa City, Iowa.

BRYANT, ERNEST C. (4) Professor of Physics, Middlebury College, Middlebury, Vt.

BUCKINGHAM, EDGAR. (20) Associate Physicist, Bureau of Standards; 2101 3d St., N.E., Washington, D. C.

BUMSTEAD, HENRY ANDREWS. (1) Professor of Physics, Sloane Laboratory, Yale University, New Haven, Conn.

BURGESS, GEORGE K. (24) Physicist, Bureau of Standards, Washington, D. C.

BURROWS, CHARLES WILLIAM. (38) Associate Physicist at Bureau of Standards; Bureau of Standards, Washington, D. C.

BURTON, E. F. (33) Associate Professor in Physics, University of Toronto, Toronto, Canada.

CADY, WALTER G. (18) Professor of Physics, Wesleyan University; 77 High St., Middletown, Conn.

CAMPBELL, GEORGE ASHLEY. (31) Research Engineer, American Telephone and Telegraph Co.; 15 Dey St., New York.

CAMPBELL, LESLIE LYLE. (31) Head Physics Department, Simmons College; 21 Ellery St., Cambridge, Mass.

CARHART, HENRY S. (1) Professor Emeritus of Physics in the University of Michigan; 211 So. El Molino Ave., Pasadena, Calif.

CARMAN, ALBERT P. (2) Professor of Physics, University of Illinois, Urbana, Ill.

CARTMEL, WILLIAM BILL. (23) 2 La Salle Rd., Verdun, Montreal, Canada.

CHAFFEE, E. L. (52) 32 Gurney St., Cambridge, Mass.

CHAMBERLAIN, CLARK WELLS. (28) President, Denison Univ., Granville, Ohio.

CHANT, CLARENCE A. (4) Associate Professor of Astrophysics, University of Toronto, Canada.

CHILD, CLEMENT D. (20) Professor of Physics, Colgate University, Hamilton, N. Y.

CLARK, A. L. (13) Queen's University; 203 Albert St., Kingston, Ontario, Canada.

CLEMENT, J. K. (39) Physicist, U. S. Bureau of Mines; 40th and Butler Sts., Pittsburgh, Pa.

COBLENTZ, WM. W. (29) Associate Physicist, Bureau of Standards, Washington, D. C.

COFFIN, JOSEPH GEORGE. (20) Assistant Professor of Physics, C. C. N. Y.; College of the City of New York, Amsterdam Ave., N. Y. City.

COHEN, LOUIS. (42) The Cliffbourne, 1847 Calvert St., Washington, D. C.

COLE, ALFRED DODGE. (20) Professor of Physics, Ohio State University, Columbus, Ohio.

COMSTOCK, DANIEL F. (40) Assistant Professor of Theoretical Physics, Massachusetts Institute of Technology, Boston.

COOK, S. R. (20) 283 Reed St., San Jose, Calif.

COOKE, HERÉWARD LESTER. (20) Assistant Professor of Physics, Princeton University; 12 Nassau St., Princeton, N. J.

COOKSEY, CHARLTON D. (31) 284 Orange St., New Haven, Conn.

COOLEY, LEROY C. (1) Professor of Physics, Emeritus; Vassar College, Poughkeepsie, N. Y.

CRAWFORD, MORRIS B. (1) Professor of Physics, Wesleyan University, Middletown, Conn.

CREHORE, ALBERT C. (31) 409 North Broadway, Yonkers, N. Y.

CREW, HENRY. (2) Fayerweather Professor of Physics, Northwestern University, Evanston, Ill.

CREIGHTON, E. E. (61) Gen. Elec. Co., Schenectady, N. Y.

CROSS, CHARLES R. (4) Professor of Physics, Mass. Institute of Technology, Boston, Mass.

CURTIS, HARVEY L. (31) Associate Physicist, Bureau of Standards, Washington, D. C.

DADOURIAN, HAROUTENE. (43) Assistant Professor of Physics, Sheffield Scientific School of Yale University, New Haven, Conn.

DANA, E. S. (2) Professor of Physics, Yale University; 24 Hillhouse Ave., New Haven, Conn.

DAVIDSON, JAMES GRANT. (40) Professor of Physics, McGill University College, Vancouver, B. C.

DAVIS, HARVEY N. (22) Assistant Professor of Physics, Harvard University, Cambridge, Mass.

DAVIS, BERGEN. (1) Assistant Professor of Physics, Columbia University, New York City.

DAY, ARTHUR L. (24) Director of the Geophysical Laboratory, Carnegie Inst. of Wash., Washington, D. C.

DAY, WILLIAM SCOFIELD. (1) Lecturer in Physics, Columbia University, New York, N. Y.; 220 Hobart Avenue, Summit, N. J.

DERR, LOUIS. (49) Professor of Physics, Massachusetts Institute of Technology, Boston, Mass.

DICKINSON, H. C. (33) U. S. Bureau of Standards, Washington, D. C.

DORSEY, H. G. (28) 1032 Grand Ave., Dayton, Ohio.

DORSEY, N. ERNEST. (2) Dept. Terrestrial Magnetism, Carnegie Institution of Washington, The Ontario, Washington, D. C.

DOUBT, THOMAS EATON. (35) Associate Professor of Physics in Armour Institute of Technology; 5402 Drexel Ave., Chicago, Ill.

DOUTY, D. E. (4) Librarian, 340 Hudson St., New York City.

DUANE, WM. (4) 1617 Land Title Building, Philadelphia, Pa.

DUFF, A. WILMER. (30) Professor of Physics, Worcester Polytechnic Institute, Worcester, Mass.

EARHART, ROBT. F. Professor of Physics, Ohio State University; Ohio State University, Columbus, Ohio.

EDMONDSON, THOMAS WILLIAM. (1) Professor of Mathematics, New York University; University Heights, New York City.

EDDY, HENRY TURNER. (26) Professor of Mathematics, University of Minnesota, Minneapolis, Minn.

EDMUNDS, Prof. C. K. (20) Canton Christian College, Honglok via Canton, China.

ERIKSON, HENRY A. (49) Assistant Professor of Physics, University of Minnesota, Minneapolis, Minn.

EWELL, ARTHUR W. (13) Professor of Physics, Worcester Polytechnic Institute, Worcester, Mass.

EWELL, MARSHALL DAVIS. (37) Rooms 618 and 619, 155 N. Clark St., Chicago, Ill.

EVE, A. S. (36) Professor of Physics, McGill University, Montreal, Canada.

FENNER, CLARENCE N. (60) Assistant Petrologist, Geophysical Laboratory, Carnegie Institution, Washington, D. C.

FERRY, ERVIN SIDNEY. (20) Professor of Physics, Purdue University; 629 South St., La Fayette. Indiana.

FISHER, WILLARD J. (30) Professor of Physics, New Hampshire College, Durham, N. H.

FISCHER, LOUIS A. (20) Physicist, Chief, Division of Weights and Measures, Bureau of Standards, Washington, D. C.

FLOWERS, ALAN E. (30) Elec. Eng. Dept., Ohio State Univ., Columbus, Ohio.

FOLEY, A. L. (4) Professor of Physics, and Head of Physics Department, Univ. of Indiana, Bloomington, Ind.

FOX, WILLIAM. (4) Associate Professor of Physics, College of the City of New York; 139th St. and Convent Ave., New York City.

FRANKLIN, W. S. (2) Professor of Physics, Lehigh University, South Bethlehem, Pa.

FULCHER, GORDON S. (34) Asst. Professor of Physics, Univ. of Wisconsin; 616 Lake St., Madison, Wis.

GALE, HENRY G. (27) Associate Professor of Physics, University of Chicago, Chicago, Ill.

GATES, FANNY COOK. (20) Professor of Physics and Dean of Women, Grinnell College, Grinnell, Iowa.

GILBERT, NORMAN E. (14) Assistant Professor of Physics, Dartmouth College, Hanover, N. H.

GOLDEN, ASHER. (4) Mechanical Engineer; 1053 Southern Boulevard, New York City.

GOODWIN, H. M. (4) Professor of Physics and Electrochemistry, Mass. Institute of Technology, Boston, Mass.

GOODSPEED, ARTHUR W. (4) Professor of Physics and Director of the Randal-Morgan Lab'y of Physics, Univ. of Pennsylvania, West Philadelphia, Pa.

GRAY, ARTHUR W. (31) Assistant Physicist, Bureau of Standards, Washington, D. C.

GORDON, CLARENCE MCCHEYNE. (22) Professor of Physics, Lafayette College, Easton, Pa.

GROVER, FREDERICK W. (38) Professor of Physics, Colby College, Waterville, Maine.

GUTHE, KARL EUGEN. (20) Professor of Physics, University of Michigan; 725 New Jersey Ave., Ann Arbor, Mich.

HAANEL, EUGENE. (4) Dept. of Interior, Ottawa, Canada.

HACHETT, FELIX E. (40) Royal College of Science, Dublin, Ireland.

HALE, GEORGE ELLERY. (4) Director, Mt. Wilson Solar Observatory, Pasadena, Cal.

HALL, ELMER E. (2) Associate Professor of Physics, University of California; 1501 LeRoy Ave., Berkeley, Calif.

HALL, EDWIN H. (2) Professor of Physics, Harvard University; 30 Landon St., Cambridge, Mass.

HAMMER, WILLIAM J. (20) Consulting Electrical Engineer; 26 Cortlandt St., New York.

HASTINGS, CHARLES S. (1) Professor of Physics, Sheffield Scientific School, Yale Univ., New Haven, Conn.

HAYFORD, J. F. (46) Director of Northwestern College of Engineering, Northwestern University; 574 Ingleside Park, Evanston, Ill.

HARRINGTON, ELMER A. (48) Smith College, Northampton, Mass.

HARTMAN, L. W. (31) Professor of Physics, Univ. of Nevada, 215 Maple St., Reno, Nev.

HAYES, H. C. (67) Jefferson Physical Laboratory, Cambridge, Mass.

HERING, D. W. (1) Professor of Physics, New York University, University Heights, New York.

HEWITT, PETER COOPER. (2) Madison Square Garden Tower, 26th St., New York.

HILL, BRUCE V. (23) Physicist, Chicago Telephone Co.; 1908 Central St., Evanston, Ill.

HOADLEY, GEORGE A. (1) Professor of Physics, Swarthmore College, Swarthmore, Pa.

HODGKINS, HOWARD L. (20) Professor of Mathematics and Physics, George Washington Univ., Washington, D. C.

HOFFMAN, SAMUEL V. (7) Morristown, N. J.

HOGG, J. L. (59) University of Toronto, Toronto, Canada.

HOTCHKISS, HOMER J. (7) Professor of Physics, Drexel Institute; 32nd and Chestnut Sts., Philadelphia, Pa.

HOWER, HARRY SLOAN. (20) Associate Professor of Physics, Carnegie Technical Schools, Pittsburgh, Pa.

HOXTON, L. G. (20) Associate Professor of Physics, University of Virginia, Charlottesville, Va.

HUBBARD, J. C. (30) Professor of Physics, Clark College, Worcester, Mass.

HUFF, WILLIAM B. (22) Professor of Physics, Bryn Mawr College, Bryn Mawr, Pa.

HULETT, G. A. (20) Professor of Physical Chemistry, Princeton University, Princeton, N. J.

HULL, GORDON FERRIE. (14) Professor of Physics, Dartmouth College, Hanover, N. H.

HUMPHREYS, W. J. (2) Professor of Meteorological Physics, U. S. Weather Bureau, Washington, D. C.

HUTCHINS, C. C. (20) Bowdoin College, Brunswick, Me.

HUTCHINSON, CARY T. (2) Consulting Engineer; 60 Wall St., New York City.

HYDE, EDWARD P. (18) Director, Physical Laboratory, National Electric Lamp Association; P. O. Drawer 387, Cleveland, Ohio.

INGERSOLL, LEONARD R. (29) Associate Professor of Physics, University of Wisconsin; Science Hall, Madison, Wis.

IVES, FREDERIC EUGENE. (37) Inventor; Weehawken P. O., N. J.

IVES, HERBERT E. (36) 3101 Passigunk Ave., Philadelphia, Pa.

IVES, JAMES E. (14) Clark University, Worcester, Mass.

JAMESON, JOSEPH MOORE. (21) Vice-President of Girard College, Philadelphia, Pa.

JOHONNOTT, E. S. (20) Professor of Physics, Rose Polytechnic Institute, 2245 North Tenth St., Terre Haute, Indiana.

JONES, HARRY CLARY. (4) Professor of Physical Chemistry, Johns Hopkins University, Baltimore, Md.

KALMUS, HERBERT T. (46) Queen's Univ., Kingston, Canada.

KANOLT, C. W. (26) Bureau of Standards, Washington, D. C.

KEITH, MARCIA A. (1) 116 Nassau St., New York, N. Y.

KENNELLY, ARTHUR E. (2) Professor of Electrical Engineering and Consulting Electrical Engineer, Harvard University, Cambridge, Mass.

KENT; N. A. (20) Professor of Physics, Boston University; 688 Boylston; St., Boston, Mass.

KESTER, FREDERICK E. (20) Professor of Physics, University of Kansas; 805 Tennessee St., Lawrence, Kansas.

KIMBALL, ARTHUR LALANNE. (1) Professor of Physics in Amherst College, Amherst, Mass.

KING, ARTHUR S. (31) Superintendent of Physical Laboratory, Mt. Wilson Solar Observatory, Pasadena, California.

KINSLEY, CARL. (27) Associate Professor of Physics, University of Chicago, Chicago, Ill.

KNIPP, CHARLES T. (7) Assistant Professor of Physics, University of Illinois; 913 W. Nevada St., Urbana, Ill.

KOVARIK, ALOIS F. (52) Instructor in Physics, Univ. of Minn., Minneapolis, Minn.

KREIDER, D. ALBERT. (43) Assistant Professor of Physics, Sloane Laboratory, Yale University, New Haven, Conn.

KUNZ, D. JAKOB. (49) Assistant Professor of Physics, University of Illinois; 308 W. Green St., Urbana, Ill.

LAIRD, ELIZABETH REBECCA. (20) Professor of Physics, Mount Holyoke College, South Hadley, Mass.

LAWRENCE, A. E. (2) Physical Research; 53 Devenshire St. (Room 12), Boston, Mass.

LEEDS, MORRIS E. (17) Manufacturer of Electrical Instruments; 4901 Stenton Ave., Philadelphia, Pa.

LEWIS, E. PERCIVAL. (20) Professor of Physics, University of California, Berkeley, Cal.

LEWIS, GILBERT N. (32) Professor of Chemistry, University of California, Berkeley, Cal.

LITTLETON, JESSE T. (65) Corning, N. Y.

LLOYD, M. G. (20) 319 S. Oak Park Ave., Oak Park, Ill.

LONGDEN, A. C. (35) Professor of Physics, Knox College, Galesburg, Ill.

LOOMIS, ELMER H. (22) Professor of Physics, Princeton University, Princeton, N. J.

LORENZ, CHAS. F. (31) P. O. D. 387, Cleveland, Ohio.

LOWATER, FRANCES. (28) Professor of Physics, Rockford College, Rockford, Illinois.

LYMAN, THEODORE. (7) Assistant Professor of Physics, Harvard University; Jefferson Laboratory, Cambridge, Mass.

LUNN, ARTHUR C. (54) Assistant Professor of Applied Mathematics, University of Chicago, Chicago, Ill.

MACKENZIE, A. STANLEY. (1) President, Dalhousie University, Halifax, N. S.

MACLAURIN, RICHARD C. (41) President, Massachusetts Institute of Technology, Boston, Mass.

MAGIE, WILLIAM FRANCIS. (1) Professor of Physics, Princeton UniversitIn Princeton, New Jersey.

MALTBY, MARGARET E. (4) Assistant Professor of Physics, Barnard College, Columbia University, New York City.

MARVIN, CHARLES FREDERICK. (38) Professor of Meteorology, U. S. Weather Bureau, Washington, D. C.

MASON, MAX. (49) Professor of Mathematical Physics, University of Wisconsin, Madison, Wis.

MATHER, W. T. (7) Professor of Physics, University of Texas, Austin, Texas.

MCCLENAHAN, HOWARD. (1) Professor of Physics, Princeton University; 16 Stockton St., Princeton, N. J.

MCCLUNG, R. K. (28) Lecturer in Physics, University of Manitoba, Winnipeg, Manitoba, Canada.

MCCOLLUM, BURTON. Bureau of Standards, Washington, D. C.

MCCOY, HERBERT N. (35) Professor of Physical Chemistry, University of Chicago, Chicago, Ill.

MCELFRESH, WILLIAM EDWARD. (20) Professor of Physics, Williams College, Williamstown, Mass.

MCKAY, THOMAS C. (31) N. M. State School of Mines, Socorro, N. Mex.

MCLENNAN, J. C. (18) Professor of Physics and Director of the Physical Laboratory, University of Toronto, Toronto, Canada.

MCNAIR, F. W. (36) President, Michigan College of Mines, Houghton, Mich.

MEES, C. L. (7) President and Professor of Physics, Rose Polytechnic Inst., Terre Haute, Ind.

MENDENHALL, C. E. (2) Professor of Physics, University of Wisconsin, Madison, Wis.

MERRILL, JOSEPH F. (37) Director State School of Mines and Professor of Physics and Electrical Engineering, University of Utah, Salt Lake City, Utah.

MERRITT, ERNEST. (1) Professor of Physics and Dean of the Graduate School, Cornell University; 39 East Ave., Ithaca, N. Y.

MERWIN, HERBERT EUGENE. (60) Assistant Petrologist Geophysical Laboratory, Washington, D. C.

MIDDLEKAUFF, GEORGE W. (20) Assistant Physicist, Bureau of Standards, Washington, D. C.

MILLER, DAYTON C. (7) Professor of Physics, Case School of Applied Science, Cleveland, Ohio.

MICHELSON, A. A. (1) Professor of Physics, University of Chicago, Chicago, Ill.

MILHAM, WILLIS I. (10) Professor of Astronomy, Williams College, Williamstown, Mass.

MILLIKAN, ROBERT ANDREWS. (22) Professor of Physics, University of Chicago, Chicago, Ill.

MILLS, JOHN. (35) Engineering Department American Telephone and Telegraph Co., Wyoming, N. J.

MILLIS, COL. JOHN. (4) U. S. Engineer's Office, Newport, R. I.

MINOR, RALPH S. (20) Associate Professor of Physics, University of California; 2745 Parker St., Berkeley, Cal.

MITCHELL, W. A. (30) , Soochon Univ., Soochon, China.

MOHLER, JOHN FRED. (4) Professor of Physics, Dickinson College; 127 S. College St., Carlisle, Pa.

MOLER, GEORGE SYLVANUS. (31) Professor of Physics, Cornell University; 408 University Ave., Ithaca, N. Y.

MORGAN, J. LIVINGSTON R. (4) Professor of Physical Chemistry, Columbia University, New York City.

MOORE, BURTON E. (20) Professor of Physics, University of Nebraska, Lincoln, Nebraska.

MOORE, JOSEPH H. (20) Lick Observatory, Mt. Hamilton, Cal.

MORE, LOUIS T. (14) Professor of Physics, University of Cincinnati, Cincinnati, Ohio.

MORSE, HARRY W. (18) Univ. of California, Berkeley, Cal.

MORSE, LEIGHTON B. (30) Instructor in Physics, Columbia University, New York City.

MUELLER, E. F. (67) 4518 9th St., Washington, D. C.

MOSS, SANFORD A. (42) Engineer Turbine Research Department, General Electric Co., Lynn, Mass.

VON NARDROFF, ERNEST R. (21) Erasmus High School, New York City; 397 Madison St., Brooklyn, N. Y.

NAYLOR, J. P. (36) Professor of Physics, DePauw University, Greencastle, Indiana.

NICHOLS, ERNEST FOX. (4) President of Dartmouth College, Hanover, N. H.

NICHOLS, EDWARD L. (1) Professor of Physics, Cornell University; 5 South Avenue, Ithaca, N. Y.

NIPHER, F. E. (4) Professor of Physics, Washington University, St. Louis, Mo.

NORTHRUP, EDWIN F. (24) Assistant Professor of Physics, Palmer Physical Laboratory, Princeton University, Princeton, N. J.

NUTTING, DR. PERLEY GILMAN. (20) Kodak Park, Rochester, N. Y.

OLSHAUSEN, GEORGE R. (27) Asst. Physicist, Bureau of Standards; 109 Shepherd St., Chevy Chase, Md.

PALMER, A. DEFOREST. (4) Associate Professor of Physics, Brown University, Providence, R. I.

PARKER, HERSCHEL C. (1) 21 Fort Green Pl., Brooklyn, N. Y.

PARSONS, LOUIS A. (20) Professor of Physics, Pennsylvania College, Gettysburg, Pa.

PATTERSON, ANDREW HENRY. (20) Professor of Physics and Astronomy, University of North Carolina, Chapel Hill, N. C.

PATTERSON, GEORGE W. (20) Professor of Electrical Engineering, University of Michigan; 1523 Washtenau Ave., Ann Arbor, Mich.

PECKHAM, WILLIAM CLARK. (22) Professor of Physics, Adelphi College, Brooklyn, New York.

PEGRAM, GEORGE B. (8) Associate Professor of Physics, Columbia University, New York City.

PEIRCE, BENJAMIN OSGOOD. (1) Hollis Professor of Mathematics and Natural Philosophy, Harvard University; The Jefferson Laboratory, Cambridge, Mass.

PERKINS, CHARLES A. (4) Professor of Electrical Engineering, University of Tennessee (also chairman of Engineering Faculty); 1547 W. Clinch Ave., Knoxville, Tenn.

PERKINS, HENRY A. (22) Professor of Physics, Trinity College; 83 Gillett St., Hartford, Conn.

PFUND, A. H. (28) Assoc. Professor of Physics; Johns Hopkins University, Box 496, Baltimore, Md.

PIERCE, C. A. (50) Worcester Poly. Inst., Worcester, Mass.

PIERCE, GEORGE W. (17) Assistant Professor of Physics, Jefferson Physical Laboratory, Harvard University, Cambridge, Mass.

PORTER, ROYAL ARTHUR. (29) Associate Professor of Physics, Syracuse University, Syracuse, N. Y.

POTTS, LOUIS M. (7) Chief Engineer, The Universal Telegraphic Co.; 107 E. Lombard St., Baltimore, Md.

PROCTOR, CHARLES A. (22) Assistant Professor of Physics, Dartmouth College, Hanover, N. H.

PUPIN, M. I. (1) Professor of Mechanical and Electrical Engineering, Columbia University, New York City.

RAMSEY, R. R. (20) Associate Professor of Physics, Indiana University; 615 E. 3rd St., Bloomington, Indiana.

RANDALL, H. M. (35) Professor of Physics, University of Michigan; 1208 Prospect St., Ann Arbor, Michigan.

RAYMOND, WILLIAM JAMES. (22) Associate Professor of Physics, University of California, Berkeley, Cal.

REED, JOHN O. (20) Professor of Physics, University of Michigan, Ann Arbor, Michigan.

REESE, HERBERT M. (27) Assistant Professor of Physics, University of Missouri, Columbia, Mo.

REICHMANN, FRITZ. (20) Room 427, Capitol, Albany, N. Y.

REID, HARRY FIELDING. (4) Professor of Dynamical Geology and Geography, Johns Hopkins University, Baltimore, Md.

RICHARDS, HORACE CLARK. (22) Professor of Mathematical Physics, University of Pennsylvania; 4812 Fairmount Ave., Philadelphia, Pa.

RICHARDSON, O. W. (35) Professor of Physics, Princeton University; 105 Fitzrandolph Rd., Princeton, N. J.

ROBINSON, L. T. (49) Gen. Elec. Co., Schenectady, N. Y.

ROBINSON, PHILIP ELY. (20) Assistant Professor of Physics, Princeton University; 37 Bank St., Princeton, N. J.

ROGERS, F. J. (20) Associate Professor of Physics, Stanford Univ.; 28 Wiggins St., Princeton, N. J.

ROSA, EDWARD B. (1) Chief Physicist, National Bureau of Standards, Washington, D. C.

RYAN, HARRIS J. (31) Professor of Electrical Engineering, Stanford University, California.

SABINE, WALLACE C. (4) Professor of Physics, Harvard University; 348 Marlborough St., Boston, Mass.

SANFORD, FERNANDO. (20) Professor of Physics, Stanford University, California.

SAUREL, PAUL L. (60) Associate Professor of Mathematics, College of City of New York, New York City.

SAUNDERS, FREDERICK A. (4) Professor of Physics, Syracuse University; 612 Ostrum Ave., Syracuse, N. Y.

SCHULTZ, L. R. (31) Officiana Meteorologica Argentina, Viamonte 640, Buenos Ayres, Argentina.

SEE, J. J. (30) Observatory, Mare Island, California.

SHEARD, CHARLES. (46) Assistant Professor of Physics, Ohio State University, Columbus, Ohio.

SHEARER, JOHN S. (1) Professor of Physics, Cornell University; 608 E. Seneca St., Ithaca, N. Y.

SHEDD, J. C. (20) Professor of Physics, Olivet College, Olivet, Mich.

SHELDON, SAMUEL. (4) Professor of Physics, Polytechnic Institute, Brooklyn, N. Y.

SHARP, CLAYTON H. (12) Test Officer, Electrical Testing Laboratories; 80th St. and East End Ave., New York City.

SHEA, DANIEL WILLIAM. (4) Professor of Physics, The Catholic University of America, Washington, D. C.

SIEG, LEE PAUL. (40) Assistant Professor of Physics, University of Iowa, Iowa City, Iowa.

SKINNER, CLARENCE A. (18) Professor of Physics, The Brace Laboratory of Physics, Univ. of Nebraska, Lincoln, Nebr.

SKINNER, C. E. (67) Westinghouse Elec. & Mfg. Co., Wilkinsburg, Pittsburgh, Pa.

ST. JOHN, C. E. (22) Research Associate, Solar Observatory of Carnegie Institution, Pasadena, Cal.

SLATE, FREDERICK. (4) Professor of Physics, University of California, Berkeley, Cal.

SLOCUM, ALLISON W. (1) Professor of Physics, University of Vermont; 295 Maple St., Burlington, Vt.

SMITH, ALPHEUS W. (31) Assistant Professor of Physics, Ohio State University, Columbus, Ohio.

SMITH, ARTHUR WHITMORE. (4) Professor of Physics, University of Michigan, Ann Arbor, Mich.

SMITH, FRANCIS H. (2) Univ. of Va., Charlottesville, Va.

SMITH, HARRISON W. (4) Associate Professor of Electrical Engineering, Massachusetts Institute of Technology, Boston, Mass.

SMITH, NEWLAND F. (29) Professor of Physics, Central University, Danville, Ky.

SNOW, BENJAMIN WARNER. (12) Professor of Physics, University of Wisconsin; 221 Langdon St., Madison, Wis.

SPENCE, BARTHOLOMEW J. (39) Princeton Univ., Princeton, N. J.

SPINNEY, L. B. (20) Professor of Physics and Illuminating Engineering, Iowa State College, Ames, Iowa.

SPRINGSTEEN, HARRY W. (22) Associate Professor of Physics, Western Reserve University, Cleveland, Ohio.

SQUIER, MAJOR GEORGE O. (28) Office of the Military Attache, American Embassy, London, England.

STEINMETZ, CHARLES P. (26) Professor of Electrical Engineering, Union University; Chief Consulting Engineer, General Electric Co., Wendall Ave., Schenectady, N. Y.

STEVENS, W. LECONTE. (2) Professor of Physics, Washington and Lee University, Lexington, Virginia.

STEVENS, JAMES STACY. (17) Professor of Physics, Dean of the College of Arts and Sciences, University of Maine, Orono, Maine.

STEWART, GEORGE W. (20) Professor of Physics, University of Iowa, Iowa City, Iowa.

STEWART, OSCAR M. (20) Professor of Physics, University of Missouri, Columbia, Mo.

STONE, MISS ISABELLE. (1) 3352 Indiana Ave., Chicago, Ill.

STRATTON, S. W. (4) Director of the National Bureau of Standards, Washington, D. C.

STRONG, DR. W. W. (36) 500 S. York St., Mechanicsburg, Pa.

SWANN, W. F. G. Physicist, Dept. of Terres. Magnetism, Carnegie Inst. of Washington, Washington, D. C.

TATNALL, ROBERT R. (20) Associate Professor of Physics, Northwestern University; 624 Lincoln St., Evanston, Ill.

TAYLOR, ALBERT HOYT. (30) Professor of Physics and Head of Department; 1415 Boulevard Ave., Grand Forks, N. D.

TAYLOR, THOS. S. (43) Sloane Laboratory, Yale Station, New Haven, Conn.

TERRY, EARLE M. (51) Assistant Professor of Physics, University of Wisconsin; 1127 Bowen Ct., Madison, Wisconsin.

THOMPSON, JOSEPH O. (2) Associate Professor of Physics, Amherst College, Amherst, Mass.

THOMSON, ELIHU. (1) Engineer, General Electric Co., Lynn, Mass.; 22 Monument Ave., Swampscott, Mass.

THWING, C. B. (14) Manufacturer of Instruments; 445 N. 5th St., Philadelphia, Pa.

TOLMAN, RICHARD C. (54) Univ. of Cal., Berkeley, Cal.

TOOL, A. Q. (53) R. R. 3, Monroe, Ia.

TROWBRIDGE, AUGUSTUS. (23) Professor of Physics, Princeton University, Princeton, N. J.

TROWBRIDGE, CHARLES C. (1) Asst. Professor Physics, Columbia University; W. 116th St., New York.

UHLER, HORACE SCUDDER. (20) Assistant Professor of Physics, Yale University; 123 Canner St., New Haven, Conn.

VAN ORSTRAND, C. E. (24) Geophysical Lab., Carnegie Inst. Washington, D. C.

VINAL, GEO. W. (47) Bureau of Standards, Washington, D. C.

VREELAND, FREDERICK K. (31) Consulting Engineer, 31 Nassau St.; Research Laboratory, 80th St. and East End Ave., New York City.

WAGGONER, C. W. (31) Prof. of Physics, Univ. of West Va., Morgantown, W. Va.

WAIDNER, CHARLES W. (2) Physicist, Bureau of Standards, Washington, D. C.

WASHBURN, E. W. (67) Univ. of Ill., Urbana, Ill.

WATERMAN, FRANK A. (1) Professor of Physics, Smith College, Northampton, Mass.

WATSON, FLOYD R. (14) Assistant Professor of Physics, University of Illinois, Urbana, Ill.

WEBB, HAROLD W. (51) Instructor in Physics, Columbia University, New York City.

WEBSTER, ARTHUR GORDON. (1) Professor of Physics, Clark University; 66 West St., Worcester, Mass.

WEINTRAUB, E. (62) Gen. Elec. Co., West Lynn, Mass.

WELLISCH, ED. W. (62) Yale Univ., Sloane Laboratory, New Haven, Conn.

WENNER, FRANK. (28) Associate Physicist, Bureau of Standards, Washington, D. C.

WENDELL, GEORGE V. (7) Professor of Physics, Columbia University, New York City.

WESTON, EDWARD. (31) President, Weston Electrical Instrument Co.; 645 High St., Newark, N. J.

WHEELER, LYNDE P. (20) Assistant Professor of Physics, Sheffield Scientific School of Yale University, New Haven, Conn.

WHEELER, E. B. (22) Professor of Physics, Clarkson School of Technology, Potsdam, N. Y.

WHITE, WALTER PORTER. (34) Physical Investigator, Geophysical Laboratory, Washington, D. C.

WHITING, SARAH FRANCES. (27) Professor of Physics, Wellesley College, Wellesley, Mass.

WHITNEY, W. R. (61) Gen. Elec. Co., Schenectady, N. Y.

WHITMAN, FRANK P. (12) Professor of Physics, Western Reserve University, Cleveland, Ohio.

WILSON, EDWIN BIDWELL. (46) Professor of Mathematics, Massachusetts Institute of Technology, Boston, Mass.

WILSON, H. A. (50) Professor of Physics, The Rice Institute, Houston, Texas.

WILCOX, GUY M. (40) Professor of Physics, Armour Institute of Technology; 5225 Ingleside Ave., Chicago, Ill.

WILLIAMS, SAMUEL R. (30) Professor of Physics, Oberlin College; 224 Woodland Ave., Oberlin, Ohio.

WILLS, ALBERT P. (8) Professor of Mathematical Physics, Columbia University, New York City.

WOLCOTT, E. R. (24) 2515 N. First St., Los Angeles, Cal.

WOLFF, FRANK ALFRED. (7) Associate Physicist, Bureau of Standards, Washington, D. C.

WOOD, R. W. (7) Professor of Physics, Johns Hopkins University, Baltimore, Md.

WOODMAN, L. E. (49) Univ. of Maine, Orono, Me.

WOODWARD, ROBERT SIMPSON. (3) President, Carnegie Institution of Washington, Washington, D. C.

WORTHING, ARCHIE G. (36) Physicist in Physical Laboratory, National Electric Lamp Association; 10940 Grantwood Ave., Cleveland, Ohio.

WRIGHT, ARTHUR W. (2) Professor of Physics, Yale University, New Haven, Conn.

WRIGHT, FRED E. (57) Petrologist, Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.

ZELENY, ANTHONY. (36) Professor of Physics, University of Minnesota, Minneapolis, Minn.

ZELENY, JOHN. (32) Professor of Physics, University of Minnesota, Minneapolis, Minn.

ASSOCIATE MEMBERS.

ADAMS, JOHN MEAD. (31) Professor of Physics, Queen's Univ., Kingston, Ontario, Canada.

AKELEY, LOUIS E. (35) Vermilion, South Dakota.

ALLISON, FRED. (49) Johns Hopkins University, Baltimore, Md.

ALEXANDER, 2d, J. W. (54) 112 Mercer St., Princeton, N. J.

ANDERSON, JOHN A. (36) Associate Professor of Astronomy, Johns Hopkins University, Baltimore, Md.

ANDERSON, W. B. (44) Associate Professor of Physics, Iowa Agricultural College; Station A, Ames, Iowa.

ANDERSON, S. HERBERT. (60) Univ. of Washington, Seattle, Wash.

ANGELL, M. T. (43) 226 E. First St., Moscow, Idaho.

ANGSTROM, A. K. (68) Fellow in Physics, Cornell University, Ithaca, N. Y.

AYRES, H. D. (28) B. F. Goodwin Rubber Co., 19 Goodwin Ave., Akron, Ohio.

BACON, GEORGE PRESTON. (41) 59 Perham St., West Roxbury Sta., Boston, Mass.

BALDWIN, J. C. (67) Hope, N. D.

BALL, ALBERT. (31) Assistant Professor of Physics and Engineering, Cooper Union, New York City.

BARBER, W. HARLEY. (43) Professor of Physics, Ripon College; 120 Thorn St., Ripon, Wisconsin.

BARDSLEY, GEORGE H. (61) University of California; 2336 College Ave., Berkeley, Cal.

BARKER, ERNEST F. (61) Instructor in Physics, University of Rochester, Rochester, N. Y.

BARSS, WM. RAYMOND. (62) Mass. Inst. Technology, Boston, Mass.

BATEMAN, GEORGE F. (46) Instructor, Department of Physics, Cooper Union, New York.

BEACH, GRACE V. (65) 141 Loring Ave., Belham, N. Y.

BEALS, FREDERICK H. (62) Barringer High School, Newark, N. J.

BIDWELL, C. C. Instructor in Physics, Cornell University, Ithaca, N. Y.

BIRCHBY, JAMES ARTHUR. (37) Professor of Physics; 229 Fourth St., Marietta, Ohio.

BIRGE, RAYMOND T. (54) Syracuse Univ. Dept. of Physics, Syracuse, N. Y.

BISHOP, E. S. (44) Instructor in Physics, University of Chicago; 5109 Greenwood Ave., Hyde Park Station, Chicago, Ill.

BISHOP, F. M. (65) 791 Yale Station, New Haven, Conn.

BLACK, N. HENRY. (31) Teacher of Physics and Chemistry, Roxbury Latin School, Boston, Mass.

BLAKE, MISS SUE AVIS. (31) Instructor in Physics, Smith College; Plymouth Inn, Northampton, Mass.

BECKNELL, GUY G. (31) Research Assistant, Clark Univ., Worcester, Mass.

BOEHM, WALTER M. (46) Instructor in Physics, Randal-Morgan Laboratory, University of Pennsylvania, Philadelphia, Pa.

BOVIE, W. T. (67) 18 Sunset St., Roxbury Crossing, Mass.

BRACKETT, WILLIAM R. (49) Instructor in Physics, University of Colorado; P. O. Box 287, Boulder, Colorado.

BRAIMIN, CLEMENT S. (34) 790 Riverside Drive, New York City.

BRANT, LAURA C. (49) Assistant in Physics, Barnard College, New York City.

BRIDGMAN, BENJAMIN W. (43) Westminster College, New Wilmington, Pa.

BRIGHTMAN, CHARLES L. (49) Instructor in Physics, Mt. Holyoke College, South Hadley, Mass.

BRIGGS, C. A. (44) Assistant Physicist, Bureau of Standards, Washington, D. C.

BROWN, BENJAMIN H. (37) Professor of Physics, Whitman College; 39 Garden City Heights, Walla Walla, Wash.

BROWN, JOSEPH G. (46) Assistant Professor of Physics, Stanford University; 1013 Ramona St., Palo Alto, Calif.

BROWN, S. L. (46) University Station, Austin, Texas.

BUCKLEY, O. E. (65) Cornell Univ., Ithaca, N. Y.

BURNS, ELEANOR I. (30) Instructor in Physics, American College for Girls, Care The Bible House, Constantinople, Turkey.

BUTMAN, CHESTER A. (49) Rockport, Mass.

CARR, M. I. (64) 5047 Winthrop Ave., Chicago, Ill.

CARTER, EDNA. (46) Assoc. Professor of Physics, Vassar College, Poughkeepsie, N. Y.

CASWELL, A. E. (46) 282 Ninth Ave., East., Eugene, Oregon.

CAVANOGH, ANGUS L. (37) High School, Los Angeles, Cal.

CHAPMAN, A. K. (60) Fellow in Physics, Princeton University, Princeton, N. J.

CHARLES, ROLLIN L. (49) Instructor in Physics, Lehigh University; 744 Seneca St., South Bethlehem, Pa.

CHASE, MABEL AUGUSTA. (57) Associate Professor Physics, Mt. Holyoke College, South Hadley, Mass.

CLARK, BERTHA MAY. (31) Director of Science, William Penn High School, Philadelphia, Pa.

CLARK, E. L. (51) 1445 Wyandotte Ave., Lakewood, Ohio.

CLARK, HARRY. (67) Jeff. Phys. Lab., Harvard Univ., Cambridge, Mass.

CLARK, HERBERT A. (29) Associate Professor of Physics, Syracuse University; 1024 Lancaster Ave., Syracuse, N. Y.

CLINKSCALES, GEO. B. (40) Montgomery, Alabama.

CLO, J. HARRY. (37) Assistant Professor of Physics, in charge of the Department of Physics, Tulane University, New Orleans, La.

COGGINS, C. L. (54) Stevens Institute of Technology, Hoboken, N. J.

COLEMAN, JAMES E. (65) Columbia Univ., N. Y.

COMPTON, KARL TAYLOR. (54) Reed College, Portland, Oregon.

COOLIDGE, WILLIAM D. (61) Assistant Director, Research Laboratory, General Electric Co., Schenectady, N. Y.

COONS, C. D. (46) Assistant Professor of Physics, Denison University, Granville, Ohio.

COOPER, FRANK LAWRENCE. (31) Instructor in Physics, 802 Yale Station, New Haven, Conn.

COPE, THOMAS D. (49) Instructor in Physics, Randal-Morgan Laboratory of Physics, Univ. of Pennsylvania, West Philadelphia, Pa.

CORNELIUS, DAVID W. (46) Physics Dept., Univ. of Kansas, Lawrence, Kansas.

CRAIGHEAD, JAMES R. (61) Electrical Engineer, General Electric Co., 39 Haigh Ave., Schenectady, N. Y.

CRANDALL, I. B. (52) The Lafayette, 137 W. 12th St., New York City.

CRAWFORD, WILLIAM WALTON. (59) General Electric Co., 9 Grant Rd., Swampscott, Mass.

CRITTENDEN, EUGENE C. (31) Assistant Physicist, Bureau of Standards, Washington, D. C.

CROOK, LOUIS H. (49) 3418 13th St., N. E., Brookland, D. C.

CULLER, J. A. (50) Professor of Physics, Miami University, Oxford, Ohio.

DAHM, THOS. M. (55) Assistant in Physics, University of Wisconsin; Science Hall, Madison, Wis.

DANCEY, LLOYD S. (48) Waukesha, Wis.

DAY, F. R. (61) McGill Univ., Montreal, Canada.

DAVIS, GRACE E. (44) Associate Professor of Physics, Wellesley College, Wellesley, Mass.

DAWES, HENRY FRANKLIN. (46) Professor of Physics; 600 Manning Ave., Toronto, Can.

DELLINGER, J. HOWARD. (42) Assistant Physicist, Bureau of Standards, Washington, D. C.

DIKE, PAUL HARRISON. (49) Professor of Physics, Cornell College, Mount Vernon, Iowa.

DITTO, R. C. (54) Department of Physics, Denison University, Granville, Ohio.

DODGE, HOMER L. (56) Assistant Instructor in Physics, State University of Iowa, Iowa City, Ia.

DUNLAP, FREDERICK. (67) Dept. of Forestry, Univ. of Missouri, Columbia, Mo.

DURWARD, ARTHUR. (31) Principal, High School, Lordsburg, California.

DUSHMAN, SAUL. Research Laboratory, General Elec. Co., Schenectady, N. Y.

DUTCHER, JOHN B. (55) Assistant Professor of Physics, Indiana University, Bloomington, Ind.

DYSART, P. M. (37) Head of Physics Department, Pittsburgh Central High School; 220 Coltart Square, Pittsburgh, Pa.

EASTHAM, MELVILLE. (51) Care of Eastham & Clapp, 729 Boylston St., Boston, Mass.

EDWARDS, CHARLES WILLIAM. (36) Professor of Physics, Trinity College, Durham, N. C.

EDWARD, MORRISON. (66) Earlham College, Richmond, Ind.

EDWARDS, H. W. (46) Baylor Univ.; 2213 Union St., Waco, Texas.

EDWARDS, P. H. (44) Allahabad Christian College, Allahabad, India.

ELDER, E. WAITE. (60) Instructor in Physics, East Denver High School, East Denver, Colo.; 1300 Pontiac St., Montclair, Colo.

ELLIS, JAMES H. (65) Mass. Inst. Tech., Boston, Mass.

ELSTON, T. S. (49) University of California, Berkeley, Calif.

EVANS, R. D. (67) Jeff. Phys. Lab., Harvard Univ., Cambridge, Mass.

FAIRBANKS, FLOYD C. (49) Instructor in Physics, Drexel Institute, Philadelphia, Pa.

FARMER, F. M. (52) 44 West 96th St., New York City.

FARWELL, HERMON W. (36) Instructor in Physics, Columbia University, New York City.

FENNINGER, WILLIAM N. (60) Dept. Physics, Pratt Institute, Brooklyn, N. Y.

FIELD, R. F. (60) Instructor in Physics, Brown University; 25 Wilson St., Providence, R. I.

FISHER, H. W. (67) Huguenot Park, Staten Island, N. Y.

FITCH, T. T. (49) Assistant Physicist, Bureau of Standards, Washington, D. C.

FLETCHER, HARVEY. (60) Professor of Physics, Brigham Young University, Salt Lake City, Utah.

FOOTE, PAUL D. (55) Asst. Physicist, Bureau of Standards, Washington, D. C.

FORSYTHE, W. E. (55) Nat. Elec. Lamp. Assoc., Cleveland, O.

FOUNTAIN, C. R. (30) Univ. of Georgia, Athens, Ga.

FRAIM, PARK B. (65) Lehigh Univ., S. Bethlehem, Pa.

FRICKEY, R. E. (50) Elec. Engineer, Northern California Power Co., Cons., Noble Elec. Steel Co., Redding, Cal.

FRY, HOWARD M. (60) Luzerne Co., Drifton, Pa.

FRYE, ROYAL M. Boston University, 94 Alder St., Waltham, Mass.

GAEHR, PAUL FREDERICK. (30) Professor of Physics, Wells College, Aurora, N. Y.

GAGE, HENRY PHELPS. (47) Physicist, Corning Glass Works, Corning, N. Y.

GAGE, O. AMSDEN. (43) Assistant Professor of Physics, University of Wisconsin; 121 W. Gilman St., Madison, Wis.

GALAJIKIAN, ALEXANDER S. (43) Assistant Professor of Mathematics, Univ. of the Philippines, Manila, Philippine Islands.

GEER, WILLIAM C. (34) Chief Chemist, The B. F. Goodrich Co., Akron, Ohio.

GERSHBERG, JOSEPH. Turbine Office, General Electric Co., Lynn, Mass.

GILCHRIST, LACHLAN. (46) Lecturer in Physics, Department of Physics, University of Toronto, Toronto, Canada.

GILLEY, F. M. (32) Chelsea High School, Chelsea, Mass.

GILROY, HELEN T. Box 22, Mt. Holyoke College, So. Hadley, Mass.

GODDARD, ROBERT H. (49) 5 Bishop Ave., Worcester, Mass.

GODFREY, WILLIAM E. (40) Professor of Physics, Mercer University, Macon, Georgia.

GOLDBERG, M. (67) 576 W. Fourth St., Dayton, O.

GOODWIN, W. N., JR. (31) Chief Electrical Engineer, Weston Electrical Instrument Co., Waverly Park, N. J.

GOUCHER, FREDERICK S. (62) Livingston Hall, Columbia University, New York City.

GOWDY, ROBERT CLYDE. (46) Instructor in Physics, Department of Physics, Lehigh University, South Bethlehem, Pa.

GRANTHAM, G. E. (67) Inst. Physics, Purdue Univ., Lafayette, Ind.

GREENE, CLARENCE WILSON. (55) Professor of Physics, Albion College, Albion, Michigan.

GREENLAW, FRANK M. (38) Head of Science Department, Rogers High School; 29 Mann Ave., Newport, R. I.

GRIFFIN, H. G. (65) Bureau of Standards, Washington, D. C.

GRONDAHL, L. O. (36) Carnegie Inst. of Technology, Pittsburgh, Pa.

GURNEY, LAWRENCE E. (35) University of Idaho, Moscow, Idaho.

HAKE, J. W. (65) Northwestern Univ., Evanston, Ill.

HALE, C. F. (67) Albany State College, Albany, N. Y.

HALEY, FRANCIS R. (57) Professor of Physics, Acadia College, Wolfville, Nova Scotia.

HAM, FRANK W. (52) State College of Agriculture, Bozeman, Mont.

HAM, WILLIAM R. (31) Professor of Physics, Pennsylvania State College; State College, Pennsylvania.

HARKINS, M. R. (60) Instructor in Physics, University of Pennsylvania, Philadelphia, Pa.

HARPER, D. ROBERTS, 3d. (31) Assistant Physicist, Bureau of Standards, Washington, D. C.

HARTMANN, F. M. (31) Professor of Electrical and Mechanical Engineering, Cooper Union, New York.

HARVEY, FREDERIC A. (31) Assistant Professor of Physics, Steele Hall of Physics; Syracuse University, Syracuse, N. Y.

HASEMAN, W. P. (31) Univ. of Oklahoma, Norman, Oklahoma.

HEAPS, CLAUDE W. (54) 13 Allen Pl., Columbia, Mo.

HEIL, H. G. (31) Instructor in Physics, Ohio State University, Columbus, Ohio.

HENDERSON, W. D. (35) University of Michigan; 1001 Forest Ave., Ann Arbor, Mich.

HENDREN, LINVILLE L. (37) Professor of Physics, University of Georgia, Athens, Ga.

HERSBERG, WALTER F. (68) Electrician; 160 E. Ontario St., Chicago, Ill.

HITCHCOCK, GEORGE G. (27) Professor of Physics, Pomona College, Claremont, California.

HOBBS, G. M. (30) Secretary American School of Correspondence; 58th and Drexel Ave., Chicago, Ill.

HODGE, PERCY. (30) Professor of Physics, Stevens Inst. of Technology, Hoboken, N. J.

HODGMAN, C. D. (46) Instructor in Physics, Case School of Applied Science, Cleveland, Ohio.

HOLLNAGEL, HERBERT P. (38) Mass. Inst. Technology,; 186 Hamilton St. Dorchester, Mass.

HORNBEAK, JOHN W. (60) 510 E. 5th St., Northfield, Minn.

HOWE, HARLEY E. (40) Randolph-Macon College, Ashland, Va.

HOYT, JOHN E. (31) 5442 Pine St., Philadelphia, Pa.

HULL, ALBERT W. (49) Instructor in Physics, Worcester Polytechnic Institute, Worcester, Mass.

HUBER, CHAS. L. (67) Y. M. C. A., Buffalo, N. Y.

HUFFORD, MASON E. (67) 6032 Kimbark Ave., Chicago, Ill.

HUNTINGTON, W. C. (49) University of Colorado, Boulder, Colorado.

HURLBURT, E. O. (68) Assistant Physicist, Johns Hopkins University, Baltimore, Md.

IRVIN, OSCAR W. (66) Toledo Univ., Toledo, Ohio.

IRVING, THOMAS P. (49) Professor of Physics, University of Notre Dame, Notre Dame, Ind.

JOHANNSSON, JOHANN G. (65) Poplar Park, via East Selkirk, Manitoba, Canada.

JOHNSON, ELBE H. (59) Instructor in Physics, University of Wisconsin, Madison, Wis.

JONES, ARTHUR TABER. (31) Iowa State College, Ames, Iowa.

JONES, LLOYD. (68) 3 Kodak Park, Rochester, N. Y.

JONES, O. H. (65) Northwestern University, Evanston, Ill.

KARRER, ENOCH. (62) Johns Hopkins University, Baltimore, Md.

KARRER, SEBASTIAN. (62) 4711 10th Ave., N. E., Seattle, Wash.

KEEBLE, WILLIAM H. (43) 5556 Ellis Ave., Chicago, Ill.

KEMBLE, EDWIN CRAWFORD. (51) 66 College House, Howard Sq., Cambridge, Mass.

KENDELL, BURTON W. (51) Care of Weston Elec. Co., 463 West St., New York City.

KERSHNER, JEFFERSON E. (37) Professor of Mathematics and Physics in Franklin and Marshall College, also Consulting Engineer; 445 W. Chestnut St., Lancaster, Pa.

KEYES, F. G. (44) Instructor in Theoretical Chemistry, Mass. Institute of Technology, Boston, Mass.

KILBY, C. M. (36) Professor of Physics and Astronomy, College Park P. O., Lynchburg, Va.

KNOLL, LLOYD MONROE. (54) Instructor in Physics, Central High School; 3262 Chestnut St., Philadelphia, Pa.

KNOWLTON, A. A. (51) Associate Professor Physics, University of Utah, Salt Lake City, Utah.

KNOWLTON, A. E. (51) Trinity College, Hartford, Conn.

KOUYOUMJIAN, H. K. (39) Consulting Engineer; 701 Commercial Building, Cleveland, Ohio.

KUEHNE, J. M. (35) Adjunct Professor of Physics, University of Texas; 716 West 23rd St., Austin, Texas.

LAKE, C. H. (49) Prin., Central High School, Hamilton, Ohio.

LANGFORD, GRACE. (57) Instructor in Physics, Barnard College, Columbia University, New York City.

LANGMUIR, IRVING. (6) Research Chemist, General Elec. Co., Schenectady, N. Y.

LAWTON, ELLIS E. (37) Elec. Eng. Dept., Syracuse University, Syracuse, N. Y.

LEE, CLAUDIUS. (39) Associate Professor of Electrical Engineering, Virginia Polytechnic Institute, Blacksburg, Va.

LEE, JOHN YIUBONG. (44) Assistant in Physics, Ryerson Physical Laboratory, University of Chicago, Chicago, Ill.

LEMON, HARVEY B. (44) Instructor in Physics, Ryerson Physical Laboratory, University of Chicago, Chicago, Ill.

LEPAGE, PROF. C. B. (49) Associate Professor of Physics, Stevens Institute of Technology, Hoboken, N. J.; Home, Stanford, Conn.

LESTER, HORACE H. (62) 190 Nassau St., Princeton, N. J.

LESTER, OLIVER C. (31) Professor of Physics, University of Colorado; 1121 Eleventh St., Boulder, Colo.

LOTKA, ALFRED J. (52) Editor of the Scientific American Supplement; 361 Broadway, New York City.

LOVING, ROBERT EDWARD. (31) Professor of Physics, Richmond College, Richmond, Virginia.

LUCKIESH, M. (60) Asst. Physicist, Physical Laboratory, National Electric Lamp Association; Box 387, 4503 Hough Ave., Cleveland, Ohio.

MCCAULEY, G. V. (55) Instructor in Physics, Northwestern University; 1029 Ayres Place, Evanston, Ill.

MCDOWELL, LOUISE SHERWOOD. (48) Associate Professor of Physics, Wellesley College; The Ridgeway, Wellesley, Mass.

MCEWEN, GEORGE FRANCIS. (46) Instructor in Mathematics, University of Illinois; Hydrographer for the San Diego Marine Biological Association; 809 W. Nevada St., Urbana, Illinois.

MCGOUGAN, ALEXANDER G. (62) 700 Yale Station, New Haven, Conn.

MACNUTT, BARRY. (31) Associate Professor of Physics, Department of Physics, Lehigh University, South Bethlehem, Pa.

MACKENZIE, DONALD. (43) Johns Hopkins University, Baltimore, Md.

MAILEY, R. D. (34) Research Laboratory Physical Chemistry, Mass. Inst. Tech.; 25 Hawthorne St., Lynn, Mass.

MAILLOUX, C. O. (31) 76 William St., New York City.

MANNING, DR. GEORGE L. (30) Professor of Physics, Robert College, Constantinople, Turkey, via England, open mail.

MARVIN, HENRY H. (51) 59 W. Adams St., Tufts College, Mass.

MASIUS, MORTON. Instructor in Physics, Worcester Polytechnic Institute, Worcester, Mass.

MAYER, EDWIN C. (59) Instructor in Physics, Cornell University, Ithaca, N. Y.

MELLENCAMP, F. J. (49) 568 Frederick Ave., Milwaukee, Wis.

MESERVEY, ARTHUR BOND. (61) Instructor in Physics, Dartmouth College, Hanover, N. H.

METCALF, W. V. (65) Fisk Univ., Nashville, Tenn.

MEYER, CHARLES F. (49) Washington University, St. Louis, Mo.

MEYER, J. FRANKLIN. (23) Associate Physicist, Bureau of Standards, Washington, D. C.

MILLER, A. H. (60) 230 Frank St., Ottawa, Canada.

MILLAR, PRESTON E. (66) Elec. Testing Laboratory, 80th & East End Ave., New York City.

MILLER, E. R. (67) Local Forecaster, U. S. Weather Bureau, Madison ,Wis.

MOLBY, FRED A. (49) 907 Atwater Ave., Bloomington, Ind.

MOODY, H. H. (67) Williamstown, Mass.

MOON, CHARLES. (67) Ithaca, N. Y.

MOORE, EDWARD J. (50) Associate Professor of Physics, 226 Woodland Ave., Oberlin, O.

MORRISON, EDWIN. (66) Earlham College, Richmond, Ind.

MURDOCK, CARLETON C. (49) Instructor in Physics, Cornell University, Ithaca, N. Y.

NASMYTH, GEORGE W. (43) 1131 Mass. Ave., Cambridge, Mass.

NELMS, W. S. (54) Georgia School of Technology, Atlanta, Ga.

NICHOLS, HAROLD W. (44) Instructor in Electrical Engineering, Armour Institute of Technology, Chicago, Ill.

NICHOLSON, P. J. (60) Antigonish, Nova Scotia, Canada.

NORRMAN, K. A. (67) 9 Portland St., Lynn, Mass.

NUSIM, M. T. (54) Assistant Engineer, Turbine Department, General Electric Co., Lynn, Mass.

NYSWANDER, R. E. (62) Professor of Physics, University of Denver, University Park, Colo.

OLMSTEAD, LEWIS B. (61) Laboratory Assistant in Physics, Bureau of Standards, Washington, D. C.

ORANGE, J. A. (67) Gen. Elec. Co., Schenectady, N. Y.

OSBORN, FREDERICK A. (35) Professor of Physics, University of Washington, Seattle, Wash.

PAGE, LEIGH. (62) 103 Brownell St., New Haven, Conn.

PALMER, FREDERIC, JR. (54) Haverford College, Haverford, Pa.

PALMER, IRVING O. (34) Prin., The Newton Tech. High School; 46 Otis St., Newtonville, Mass.

PARTRIDGE, EDWARD A. (54) Professor of Physics, W. Philadelphia High School, Philadelphia, Pa.

PARMLY, CHARLES H. (43) Associate Professor of Physics, The College of the City of New York, New York City.

PATTERSON, ROBERT A. (62) Bristol, Conn.

PERKINS, PERRY B. (42) Professor of Physics, Howard University, Washington, D. C.

PERLEY, F. G. (60) Instructor in Physics, Lehigh University, South Bethlehem, Pa.

PETROSKY, V. (49) 1826 Delaware St., Berkeley, Cal.

PHELPS, W. A. (67) Dartmouth College, Hanover, N. H.

PIENKOWSKY, ARTHUR. (61) Chevy Chase, Md.

PLIMPTON, SAMUEL J. (62) Johns Hopkins Univ., Baltimore, Md.

POMEROY, J. C. (46) Univ. of Iowa, Iowa City, Ia.

PORTER, THOMAS LANSING. (49) Univ. of Cincinnati, Cincinnati, Ohio.

POWER, C. E. (66) 804 E. Seneca St., Ithaca, N. Y.

POWERS, WALLACE F. (61) Clark University, Worcester, Mass.

PRATT, W. H. (62) Instrument Designing Engineer, General Electric Co., Schenectady, N. Y.

RAFFERTY, REV. PATRICK. (66) 761 Harrison Ave., Boston, Mass.

RANDALL, J. A. (59) Pratt Institute, Brooklyn, N. Y.

RANDOLPH, O. A. (65) Univ. of Illinois, Urbana, Ill.

RANKIN, HERBERT E. (59) Cherry Hill, Albany, N. Y.

RATLIFF, R. F. (66) Central Normal College, Danville, Ind.

REED, TAYLOR. (61) General Electric Co., Schenectady, N. Y.

REIGHLEY, H. H. (66) 2088 Tuller St., Columbus, O.

REUTSCHLER, HARVEY C. (44) Assistant Professor of Physics, University of Missouri; 306 South 5th St., Columbia, Mo.

RICH, D. L. (66) Phys. Dept. Univ. of Michigan, Ann Arbor, Mich.

RICHTMYER, F. K. (31) Assistant Professor of Physics, Cornell University; Ithaca, N. Y.

ROBERTSON, JOHN K. (50) School of Mining, Kingston, Canada.

ROEBUCK, JOHN R. (43) Instructor in Physics; 1226 Mound St., Madison, Wis.

ROOP, WENDELL PRESCOTT. (46) Dept. Physics, Univ. of California, Berkeley, Cal.

ROSS, P. A. (46) Instructor in Physics, Stanford University, California.

RYSGAARD, JENS. (60) 715 N. 6th St., Grand Forks, N. D.

ST. JOHN, ANCEL. (68) Instructor in Physics, Worcester Polytechnic Institute; 53 Queen St., Worcester, Mass.

SATTERLY, D. JOHN. (65) Univ. of Toronto, Toronto, Canada.

SAWTELLE, W. (64) Haverford College, Haverford, Pa.

SAYRE, HERBERT ARMISTEAD. (37) Professor of Mathematics, University, Alabama.

SCHELLENS, C. A. (60) 56 Baltimore St., Lynn, Mass.

SCHUDDENMAGEN, CONRAD L. B. (31) 7228 Coles Ave., Chicago, Ill.

SCHULTE, E. D. N. (25) Rensselaer Polytechnic Institute, Troy, N. Y.

SCHULTZ, WM. F. (23) Assistant Professor of Physics, Univ. of Illinois; 926 W. Green St., Urbana, Illinois.

SEVERINGHAUS, W. L. (54) Instructor in Physics, Fayerweather Hall, Columbia University, New York City.

SHANNON, JAMES I. (68) Assistant Professor, St. Louis University, St. Louis, Mo.

SHAW, A. N. (50) 422 Elm Ave., Westmont, Montreal, Canada.

SHOOK, GLENN A. (40) University of Illinois, Urbana, Ill.

SILVEY, O. W. (67) 244 Harrison St., W. La Fayette, Ind.

SILSBEE, F. V. (65) Bureau of Standards, Washington, D. C.

SLEATOR, W. W. (65) University of Michigan, Ann Arbor, Mich.

SIMPSON, FRANK M. (23) Professor of Physics, Bucknell College, Lewisburg, Pa.

SMITH, CHARLES HENRY. (33) Head, Department of Science, Hyde Park High School, Editor School Science and Mathematics; 5406 Madison Ave., Chicago, Ill.

SMITH, CHARLES MARQUIS. (40) Assistant Professor of Physics, Purdue University; 910 S. Ninth St., La Fayette, Indiana.

SMITH, KEITH K. (54) Garrett, Ind.

SMITH, ORRIN H. (54) Assistant in Physics, University of Illinois; 710 W. Stoughton St., Urbana, Ill.

SMITH, T. TOWNSEND. (61) Instructor, University of Kansas; 941 Indiana St., Lawrence, Kansas.

SNOW, CHESTER. (66) Physics Dept., University of Wisconsin, Madison, Wis.

SNYDER, ROBERT E. (51) Case School of Applied Science, Cleveland, O.

SOMERVILLE, A. A. (51) U. S. Rubber Co., General Laboratories, 11th Ave. & 58th St., New York City.

SOUDER, WM. H. (68) Bureau of Standards, Washington, D. C.

SPARROW, CARROLL MASON. (40) Adjunct Professor of Physics, University of Va., Charlottesville, Va.

SPONNER, C. C. (44) 146 W. Hewitt Ave., Marquette, Mich.

STACK, ERWIN B. (66) Monroe, N. C.

STEPHENSON, EDWARD BEATTIE. (44) Instructor in Physics, University of North Dakota, Grand Forks, North Dakota.

STETSON, HAROLD TRUE. (61) Dearborn Observatory, Northwestern University, Evanston, Ill.

STEVENS, LUCY M. Instructor in Physics, Wellesley College, Wellesley, Mass.

STEWART, MAUDE S. (36) 410 Winona St., Northfield, Minn.

STIFLER, W. W. (39) Assistant in Physics, Fayerweather Hall, Columbia University, New York City.

STILES, HAROLD. (44) Professor of Physics, Morningside College; 1714 Third Ave., Sioux City, Iowa.

STIMSON, HAROLD S. (61) Clark University, Worcester, Mass.

STOEKLE, E. R. (60) Assistant in Physics, Science Hall, University of Wisconsin, Madison, Wis.

STRADLING, GEORGE F. (36) Head of Science Department, Northeast Manual Training High School; 8th St. and Lehigh Ave., Philadelphia, Pa.

STUHLMANN, OTTO, JR. (40) Lab. of Physics, Univ. of Pennsylvania, Philadelphia, Pa.

SWANN, CLIFFORD M. (26) 600 W. 145th St., New York City.

TATE, J. T. (61) Univ. of Nebraska, Lincoln, Neb.

TAYLERSON, EWART S. (54) Room 54, 1 East 42nd St., New York City.

TAYLOR, JOHN BELLAMY. (42) Engineer, Foreign Department, General Electric Co.; 7 Adams Road, Schenectady, N. Y.

THOMAS, PHILLIPS. (43) 901 South Ave., Wilkinsburg, Pa.

THOMPSON, GORDON. (55) Electric Testing Laboratories; 80th St. and East End Ave., New York City.

TIDD, G. W. (66) Kansas State Normal School, Emporia, Kansas.

TIMMERMAN, CHARLES E. (23) Chairman, Department of Physics, DeWitt Clinton High School, New York City.

TRUEBLOOD, H. M. (67) Jeff. Phys. Lab., Harvard University, Cambridge, Mass.

TRUESDELL, W. B. (65) Tutor in Physics, College of the City of New York, New York City.

TUGMAN, DR. OREN. 3 Kodak Park, Rochester, N. Y.

TURNER, E. T. (30) Ithaca, N. Y.

TWISDEN, HARRY SAMUEL. (52) 9 Harwood Ave., E. Saugus, Mass.

ULREY, CLAYTON. (65) Columbia Univ., New York City.

VAWTER, C. E. (36) Head of Department of Physics, Virginia Polytechnic Institute, Blacksburg, Va.

VAUGHAN, LENA. (31) Professor of Physics, Mississippi Industrial Institute and College; 1021 Main St., Columbus, Miss.

WAKE, W. S. (66) 410 W. North St., Galesburg, Ill.

WEBSTER, DAVID. (65) 2 Walnut St., Boston, Mass.

WEBSTER, EVANS. (38) 11 Sachem Terrace, Lynn, Mass.

WEBSTER, E. H. (43) Atlanta University, Atlanta, Ga.

WEIBEL, ERNEST. (60) Asst. Physicist, Bureau of Standards, Washington, D. C.

WEINLAND, CLARENCE R. (67) 381 W. 10th Ave., Columbus, Ohio.

WELD, LEROY D. (65) Professor of Physics, Coe College, Cedar Rapids, Ia.

WENIGER, WILLIBALD. (43) Professor of Physics, Oregon Agricultural College, Corvallis, Oregon.

WENRICH, C. N. (60) Asst. Prof. of Physics, University of Pittsburgh, Pittsburgh, Pa.

WESTHAFER, WM. R. (61) Instructor in Physics, Amherst College; 9 Woodside Ave., Amherst, Mass.

WETZEL, R. A. (66) Physics Dept., College of City of New York, New York City.

WHEELER, NATHANIEL E. (61) Senior Demonstrator in Physics, Macdonald Physics Bldg., McGill University, Montreal, Canada.

WHITEHORNE, WILLIAM R. (39) Professor of Physics, Bates College, 55 Cottage St., Lewiston, Me.

WICK, FRANCES G. (36) Instructor in Physics, Vassar College, Poughkeepsie, N. Y.

WILLIAMS, ELMER H. (53) Instructor in Physics, University of Illinois; 708 W. Stoughton St., Urbana, Ill.

WILLIAMS, DR. H. B. (65) Columbia University, New York City.

WILLIAMS, N. H. (55) University of Michigan; 1020 Olivia Ave., Ann Arbor, Mich.

WILY, J. H. (49) Lehigh University, South Bethlehem, Pa.

WINCHESTER, GEORGE. (50) Professor of Physics, Washington and Jefferson College, Washington, Pa.

WOODBURY, D. A. (60) 634 Cabot St., Beverly, Mass.

WOODROW, JAY W. (55) 917 St. Mark's Ave., Brooklyn, N. Y.

WRIGHT, W. R. (66) Physics Dept., Columbia University, New York City.

WYNNE, PHILIP H. (37) Consulting Engineer, Deerfield, Mass.

YORK, FRED R. (65) University of Iowa, Iowa City, Iowa.

ZOBEL, O. J. (60) University of Wisconsin, Madison, Wis.

INDEX TO VOLUME II., SERIES II.

A.

Absorbers, A Direct Method of Finding the Value of Materials as Sound, *Hawley O. Taylor*, 270.

Air, The Flow of, through Capillary Tubes, *I. M. Rapp*, 363.

Alternating Current Testing, Some Integrating Methods in, *Frederick Bedell*, 404.

American Physical Society:
Abstracts, 77, 503.
List of Members, 507.
Minutes, 400.

Arc, Rotations in the Iron, *W. G. Cady*, 249.

Avogadro Constant, On the Elementary Electrical Charge and the, *R. A. Millikan*, 109.

Ayres, H. D., The Refraction of Gases at Different Temperatures and Pressures, 161.

B.

Barnett, S. J., On Electromagnetic Induction, 323.

Bedell, Frederick, Some Integrating Methods in Alternating Current Testing, 404.

Binaural Localization, The Significance of Intensity-Sum in, *G. W. Stewart*, 72.

Bolometer, A Balanced Method of Using the, *Irving B. Crandall*, 343.

Book, Wm. I., An Electric Converter, 49.

Bridgman, P. W., Change of State Solid-Liquid at High Pressures, 401.

Brown, F. C., The Action of Mercury Vapor on Selenium, 153.
The Sensibility Curves for Selenium; a New Sensibility-Wave-Length Maximum and a New Principle, 487.
A Practical Electrical Method of Measuring the Distance between Parallel Conducting Planes, with Application to the Question of the Existence of Electron Atmospheres, 314.

Burbridge, Harry C., The Thermal Coefficient of Contact Electromotive Force, 183.

Burgess, G. K., Some Characteristics of Total Radiation Pyrometers, 77.
Some Measurements with the Micropyrometer, 77.
The Critical Ranges A_2 and A_3 of Pure Iron, 404.

C.

Cady, W. G., Rotations in the Iron Arc, 249.

Canal Rays, The Transmission of, through Thin Partitions, *Alfred N. Goldsmith*, 16.

Capillary Tubes, The Flow of Air through, *I. M. Rapp*, 363.

Cathode Films, The Photoelectric Properties and Contact Resistances of Thin, *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 199.
Films, The Photoelectric Properties and Contact Resistances of Thin, II., *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 327.
Ray Line, On the Beaded Character of the, as Revealed by Instantaneous Photographs taken at Short Range, *Chas. T. Knipp*, 39.
Rays, A Determination of e/m and v by the Measurement of a Helix of Wehnelt, *J. B. Nathanson*, 307.
Spray, Silvered Quartz Fibers of Low Resistance obtained by, *Horatio B. Williams*, 402.

Change of State Solid-Liquid at High Pressures, *P. W. Bridgman*, 401.

Coaxial Circles, Extension of Maxwell's Series Formula for the Mutual Inductance of, *J. G. Coffin*, 65.

Coffin, J. G., Extension of Maxwell's Series Formula for the Mutual Inductance of Coaxial Circles, 65.

Compton, Karl T., The Photoelectric Properties and Contact Resistances of Thin Cathode Films, 199.
The Photoelectric Properties and Contact Resistances of Thin Cathode Films, II., 327.

Conductivity, Thermal, of Air at Low Pressures, *A. Trowbridge*, 58.

Conductivities, Thermal and Electrical, of the Alkali Metals, *J. W. Hornbeck*, 217.

Contact Resistances and Photoelectric Properties of Thin Cathode Films, *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 199.
and Photoelectric Properties of Thin Cathode Films, *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 327.

Coolidge, W. D., A Powerful Röntgen Ray Tube with a Pure Electron Discharge, 409.

Converter, An Electric, *Wm. I. Book*, 49.

Copper Wire, The Change in the Elasticity of a, with Current and External Heating, *H. L. Dodge*, 431.

Crandall, Irving B., The Infra-red Optical Properties of Some Sulphides: A Balanced Method of Using the Bolometer, 343.

Critical Ranges A_2 and A_3 of Pure Iron, *G. K. Burgess* and *J. J. Crowe*, 404.

Crowe, J. J., The Critical Ranges A_2 and A_3 of Pure Iron, 404.

D.

Dodge, H. L., The Change in the Elasticity of a Copper Wire with Current and External Heating, 431.

E.

Electrical Charge, On the Elementary, and the Avogadro Constant, *R. A. Millikan*, 109.

Resistance, Change in, Due to the Orientation of Oblate Spheroids within the Conductor, Comparative Studies of Magnetic Phenomena, V., *S. R. Williams*, 241.

Electromagnetic Induction, *S. J. Barnett*, 323.

Electron Atmospheres, A Practical Electrical Method of Measuring the Distance between Parallel Conducting Planes, with Application to the Question of the Existence of Electron Atmospheres, *F. C. Brown*, 314.

Discharge, A Powerful Röntgen Ray Tube with a Pure, *W. D. Coolidge*, 409.

Emissivity of Oxidized Metallic Surfaces, *C. P. Randolph*, 144.

Expansion, The Reversible Adiabatic, of Water, *J. R. Roebuck*, 299.

F.

Foote, P. D., Some Characteristics of Total Radiation Pyrometers, 77.

G.

Gases, The Refraction of, at Different Temperatures and Pressures, *H. D. Ayres*, 161.

Goldsmith, Alfred N., The Transmission of Canal Rays through Thin Partitions, 16.

H.

Hennings, Albert E., A Critique and Study on the Nature of the Volta Effect, 1.

Hornbeck, J. W., Thermal and Electrical Conductivities of the Alkali Metals, 217.

I.

Infra-red Optical Properties of Some Sulphides, *Irving B. Crandall*, 343.

Integrating Methods, Some, in Alternating Current Testing, *Frederick Bedell*, 404.

Intensity, The Significance of, Sum in Binaural Localization, *G. W. Stewart*, 72.

Ionization, On Temperature and Surface Conditions which Affect the Positive, from Heated Platinum, *Charles Sheard* and *D. A. Woodbury*, 288.

K.

Klopsteg, Paul E., The Measurement of Magnetic Fields by their Damping Effect upon a Vibrating Coil, 390.

Knipp, Chas. T., On the Beaded Character of the Cathode Ray Line as Revealed by Instantaneous Photographs taken at Short Range, 39.

L.

Langmuir, Irving, The Effect of Space Charge and Residual Gases on the Thermionic Current in High Vacuum, 402.

The Effect of Space Charge and Residual Gases on Thermionic Currents in High Vacuum, 450.

The Vapor Pressure of Metallic Tungsten, 329.

M.

Magnetic Fields, The Measurement of, by their Damping Effect upon a Vibrating Coil, *Paul E. Klopsteg*, 390.

Magneto-Optical Parameters of Iron and Nickel, *Chester Snow*, 29.

Magnetic Phenomena, Comparative Studies of, V., Change in Electrical Resistance Due to the Orientation of Oblate Spheroids within the Conductor, *S. R. Williams*, 241.

Mechanical Equivalent of Heat, A Porous Plug for the, *J. R. Roebuck*, 79.

Mercury Vapor, The Action of, on Selenium, *F. C. Brown*, 153.

Metallic Surfaces, The Emissivity of Oxidized, *C. P. Randolph* and *M. J. Overholser*, 144.

Metals, Thermal and Electrical Conductivities of the Alkali, *J. W. Hornbeck*, 217.

Micropyrometer, Some Measurements with the, *G. K. Burgess* and *R. G. Waltenberg*, 77.

Millikan, R. A., On the Elementary Electrical Charge and the Avogadro Constant, ~~190~~ 109

Moffitt, G. W., A Study of Some Changes in the Air-Liquid Contact Potential Difference, 95.

Mutual Inductance, Extension of Maxwell's Series Formula for the, of Coaxial Circles, *J. G. Coffin*, 65.

N.

Nathanson, J. B., A Determination of e/m and v by the Measurement of a Helix of Wehnelt Cathode Rays, 307.

O.

Overholser, M. J., The Emissivity of Oxidized Metallic Surfaces, 144.

P.

Photoelectric Properties and Contact Resistances of Thin Cathode Films, *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 199.

Photo-electric Cells, Note on Potential Attained by, in Darkness, *J. W. Woodrow*, 198.

Photo-electric Properties and Contact Resistances of Thin Cathode Films, *Otto Stuhlmann, Jr.*, and *Karl T. Compton*, 327.
Planes, A Practical Electrical Method of Measuring the Distance between Parallel Conducting, with Application to the Question of the Existence of Electron Atmospheres, *F. C. Brown*, 314.
Plug Method, A Porous, for the Mechanical Equivalent of Heat, *J. R. Roebuck*, 79.
Potential Difference, The Longitudinal Thermomagnetic, *Alpheus W. Smith*, 383.
A Study of Some Changes in the Air-Liquid Contact, *G. W. Moffitt*, 95.
Primary Current, Conditions Involving a Decrease of, with Increasing Secondary Current, *F. J. Rogers*, 503.

R.

Radiation Pyrometers, Some Characteristics of Total, *G. K. Burgess* and *P. D. Foote*, 77.
Randolph, C. P., The Emissivity of Oxidized Metallic Surfaces, 144.
Rapp, I. M., The Flow of Air through Capillary Tubes, 363.
Relativity Theory; The Equipartition Law in a System of Particles, *Richard C. Tolman*, 506.
General Dynamical Principles, *Richard C. Tolman*, 505.
Residual Gases, The Effect of Space Charge and, on Thermionic Current, *Irving Langmuir*, 402.
Roebuck, J. R., A Porous Plug Method for the Mechanical Equivalent of Heat, 79.
The Reversible Adiabatic Expansion of Water, 299.
Rogers, F. J., Conditions Involving a Decrease of Primary Current with Increasing Secondary Current, 503.
Röntgen Ray Tube, A Powerful, with a Pure Electron Discharge, *W. D. Coolidge*, 409.
Roop, W. P., The Magnetic Susceptibility of Gases, 497.

S.

Sanford, Fernando, On the Nature of the Volta Effect, 495.
Selenium, The Action of Mercury Vapor on, *F. C. Brown*, 153.
The Sensibility Curves for; a New Sensibility-Wave-Length Maximum and a New Principle, *F. C. Brown* and *L. P. Sieg*, 487.
Sensibility Curves, The, for Selenium; a New Sensibility-Wave-Length Maximum and a New Principle, *F. C. Brown* and *L. P. Sieg*, 487.
Sheard, Charles, On Temperature and Surface Conditions which Affect the Positive Ionization from Heated Platinum, 288.
Sieg, L. P., The Sensibility Curves for Selenium; a New Sensibility-Wave-Length and a New Principle, 487.
Slate, Frederick, Vector Potential in Relation to Vector Angle, 211.
Smith, Alpheus W., The Longitudinal Thermomagnetic Potential Difference, 383.
Snow, Chester, The Magneto-Optical Parameters of Iron and Nickel, 29.
Space Charge, The Effect of, and Residual Gases on the Thermionic Current, *Irving Langmuir*, 402.
Stewart, G. W., The Significance of Intensity-Sum in Binaural Localization, 72.
Stuhlmann, Jr., Otto, The Photoelectric Properties and Contact Resistances of Thin Cathode Films, II., 327.
The Photoelectric Properties and Contact Resistances of Thin Cathode Films, 199.
Sulphides, The Infra-red Optical Properties of Some, A Balanced Method of Using the Bolometer, *Irving B. Crandall*, 343.
Susceptibility, The Magnetic, of Gases, *W. P. Roop*, 497.

T.

Taylor, Hawley O., A Direct Method of Finding the Value of Materials as Sound Absorbers, 270.
Thermal Coefficient of Contact, Electromotive Force, *Harry C. Burbridge*, 183.
Thermionic Current, The Effect of Space Charge and Residual Gases on the, in High Vacuum, *Irving Langmuir*, 402.
Currents, The Effect of Space Charge and Residual Gases on, in High Vacuum, *Irving Langmuir*, 350.
Thermomagnetic Potential Difference, The Longitudinal, *Alpheus W. Smith*, 383.
Tolman, Richard C., Relativity Theory; General Dynamical Principles, 505.
Relativity Theory; The Equipartition Law in a System of Particles, 506.
Trowbridge, A., Thermal Conductivity of Air at Low Pressures, 58.
Tungsten, The Vapor Pressure of Metallic, *Irving Langmuir*, 329.

V.

Vector Angle, Vector Potential in Relation to, *Frederick Slate*, 211.
Potential in Relation to Vector Angle, *Frederick Slate*, 211.
Volta Effect, On the Nature of the, *Fernando Sanford*, 495.
A Critique and Study on the Nature of the, *Albert E. Hennings*, 1.

W.

Waltenberg, R. G., Some Measurements with the Micropyrometer, 77.

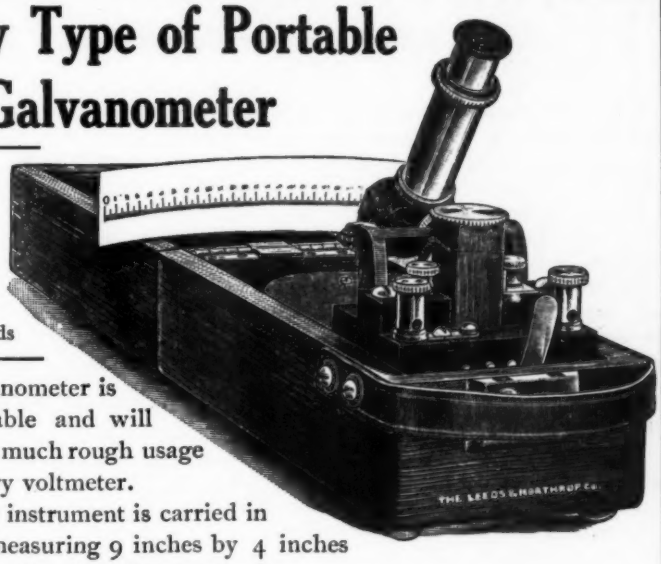
Williams, Horatio B., Silvered Quartz Fibers of Low Resistance Obtained by Cathode Spray, 402.

Williams, S. R., Comparative Studies of Magnetic Phenomena, V., Change in Electrical Resistance Due to the Orientation of Oblate Spheroids within the Conductor, 241.

Woodbury, D. A., On Temperature and Surface Conditions which Affect the Positive Ionization from Heated Platinum, 288.

Woodrow, J. W., Note on Potential Attained by Photo-electric Cells in Darkness, 198.

A New Type of Portable Galvanometer



Sensitivity
20 megohms

Resistance
about 225 ohms

Period
about 2 seconds

This galvanometer is strictly portable and will withstand as much rough usage as an ordinary voltmeter.

The entire instrument is carried in an oak box measuring 9 inches by 4 inches by 4 inches and weighs but 9 pounds.

When the case is to be closed the telescope is moved into a position parallel to the long axis of the box.

The illustration shows an Ayrton Universal Shunt and a standard 100,000 ohms resistance mounted in the instrument for use in insulation testing.

The moving system is mounted in a separate unit. This is shown full size in the lower illustration. Should repairs to the system ever be necessary, this unit can be readily returned by mail, its weight being but 4 ounces.

Bulletin No. 240 contains a complete description of this instrument. A copy will be sent upon request.

The Leeds & Northrup Co.

Electrical Measuring Instruments

4900 Stenton Ave.,

PHILADELPHIA

THE PHYSICAL REVIEW

Information for Contributors.

1. All correspondence relating to contributions should be addressed to THE PHYSICAL REVIEW, Ithaca, N. Y. Manuscripts will be acknowledged as soon as received. Articles submitted for publication in the REVIEW are not to be submitted for publication elsewhere, unless the authorization of the editors has been obtained, and, in case of duplicate publication in English, proper reference to the REVIEW is made. Manuscript should be ready for the printer; the editors cannot assume responsibility for its correctness. The presentation should be as concise as is consistent with clearness; all unnecessary duplication of data in tables and in curves is to be avoided, and tabular matter should be introduced *in extenso* only when the exact numerical values affect the value of the paper. It is requested that the metric system be used in all cases. Whenever the value of a quantity is expressed in any other system, its value in the metric system should be added in parentheses.

To insure prompt attention during the summer, manuscripts should be submitted by June 15.

2. Illustrations should be in black and white and should be ready for direct reproduction; such illustrations will be made without expense to the author. The ink used in preparing illustrations should be *jet black*. Curves can be satisfactorily reproduced when plotted on plain paper or on blue-lined cross-section paper; co-ordinates may be ruled in black at desired intervals, for example every centimeter or every inch. Blue lines are not reproduced photographically; *colors other than jet-black and blue should be avoided*. The material in an illustration should be compactly arranged; when it is much spread out, a greater reduction is necessary in reproduction. Lettering on illustrations should be plain and of sufficient size to be legible after reduction.

It is generally desirable to refer to *all* illustrations as "figures," designated by one consecutive series of numbers. The location of each figure should be marked in the manuscript, together with any caption which is to be printed beneath it.

3. A proof of each contributed article will be sent to the author for his approval. It is requested that all proof be returned promptly. Authors should note that cross references can not well be made by page number, for a change in paging is often necessary in the final make-up.

Although proof of abstracts can usually be submitted to authors, this is not always possible without delay in publication; in the case of abstracts, therefore, it is particularly important that the manuscript be free from error. In revising proof of abstracts, authors should correct any errors of the printer, but should make no changes that will affect the arrangement of paging.

4. Offprints, ordered on the proper form with return of proof, will be furnished by the printer according to the prices given below. Any special instructions in regard to offprints,—special title page, etc.,—should be indicated on the order to the printer (or attached thereto) and not as a letter to the editors. (Further inquiries in regard to offprints may be addressed to The New Era Printing Co., Lancaster, Pa.)

CHARGE FOR OFFPRINTS

Copies	4 pp.	8 pp.	12 pp.	16 pp.	20 pp.	24 pp.	28 pp.	32 pp.	48 pp.	64 pp.
50	$1.45	$1.95	$2.60	$2.92	$3.67	$4.30	$5.20	$5.70	$8.10	$10.60
75	1.60	2.30	3.05	3.45	4.70	4.95	6.10	6.60	9.45	11.05
100	1.80	2.60	3.50	3.95	5.10	5.90	7.00	7.50	10.85	13.05
150	2.05	3.05	4.20	4.85	6.75	6.95	7.35	9.15	13.20	17.55
200	2.35	3.75	5.25	6.15	7.85	8.75	10.45	11.05	16.35	21.65
300	2.95	4.75	5.85	8.15	10.60	11.90	14.10	14.85	22.15	29.55

Covers: 50 covers for $1.00, and 1c. for each additional cover.

You might write for our Cross Section Sample Book now

This booklet is worth having on file. Many times we think we do not need an article and so forget to have information on file. You will know the kinds available if you have our sample book. We can fill orders on short notice.

Cornell Co-operative Society

Morrill Hall **Ithaca, New York**

Weston=A=C=Instruments

WATTMETER
Single and Polyphase

SYNCHROSCOPE

VOLTMETER

A Complete Line of Alternating Current Switchboard Indicating Instruments

EVERY detail of each of these instruments has been most carefully studied and worked out so as to be sure that each shall fully meet the most exacting requirements of the service for which it is intended. Neither pains nor expense has been spared in the effort to produce instruments having the longest possible life, the best possible scale characteristics, combined with great accuracy under the most violent load fluctuations, and also under the many trying conditions met with in practical work. Every part of each instrument is made strictly to gauge and the design and workmanship and finish is of the highest order of excellence.

FREQUENCY METER

POWER-FACTOR METER

AMMETER

Full particulars of design, construction, prices, etc., are given in Catalogue 16
Write for it

Weston Electrical Instrument Co.

Waverly Park **Newark, N. J.**

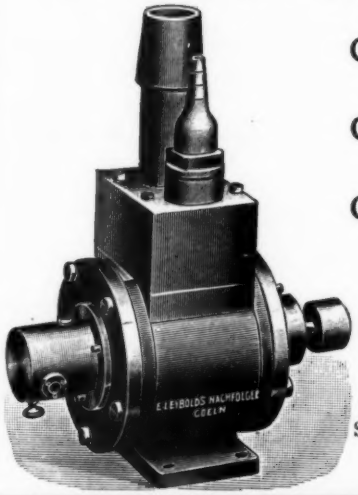
New York . . . . . 114 Liberty Street
Chicago . . . . . 1504 Monadnock Block
Boston . . . . . 176 Federal Street
Birmingham . . . . . Brown Marx Building
Philadelphia . . . . . 342 Mint Arcade
Detroit . . . . . 44 Buhl Block
St. Louis . . . . . 015 Olive Street
Denver . . . . . 231 Fifteenth Street
San Francisco . . . . . 682 Mission Street
New Haven . . . . . 29 College Street
Cleveland . . . . . 1729 E. 12th Street

E. LEYBOLD'S NACHFOLGER,

COLOGNE (Germany)

Sole Manufacturers of

Dr. Gaede's High Vacuum Pumps



Gaede's Rotary Box Pump

evacuates to .005 mm.

Gaede's Mercury Pump

evacuates to .00001 mm.

Gaede's Molecular Pump

Entirely new working principle.

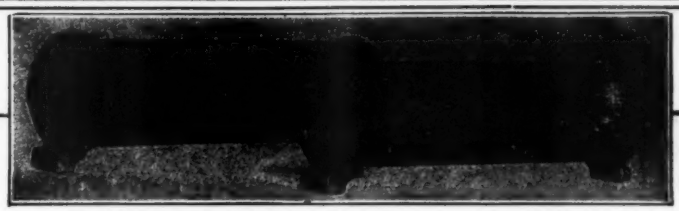
Most rapid action.

Without mercury and drying agents.

It pumps vapors as well as gases.

It evacuates to .000001 mm. and more.

See description in Nature, No. 2256, Vol. 90, page 574.



RESISTANCE UNITS

FOR ALL PURPOSES

The Cutler-Hammer Mfg. Co. has developed resistances for every kind of service.

Our Carpenter enclosed resistances are extremely compact in construction and are well suited for service in damp and dirty locations and where temporary overloads occur.

The Wirt Calibrating Rheostats are adapted for work requiring fine variations of high resistance as in laboratory or calibration work.

Our catalog lists hundreds of styles and sizes of resistance units.

Send to our nearest office for further information.

THE CUTLER-HAMMER MFG. CO.

MILWAUKEE

NEW YORK: Hudson Terminal, 50 Church St. CHICAGO: Monadnock Block. PITTSBURG: Farmers Bank Bldg. BOSTON: 176 Federal St. PHILADELPHIA: 1207 Commonwealth Trust Bldg. CLEVELAND: 1108 Schofield Bldg. Pacific Coast Agents: Messrs. Otis & Squires, 155 New Montgomery St., SAN FRANCISCO, CAL.

LEPPIN & MASCHE

BERLIN, S.O., GERMANY **17 ENGELUFER.**

Factory of Scientific Instruments

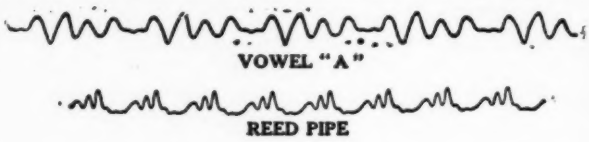
Apparatus for a novel method of demonstrating the varying curves of sound waves upon a screen (acoustic oscillograph).

1\ **Stand with Sound Box, two Mirrors, and Horn with Bell Mouth, $20.50.**

2) **Rotating Mirror, Precision Instrument, $15.50.**

Whirling Table with Heavy Wheel, $13.10.

3) **Lantern Slides of Curves taken by F.F.Martens and O.Leppin**



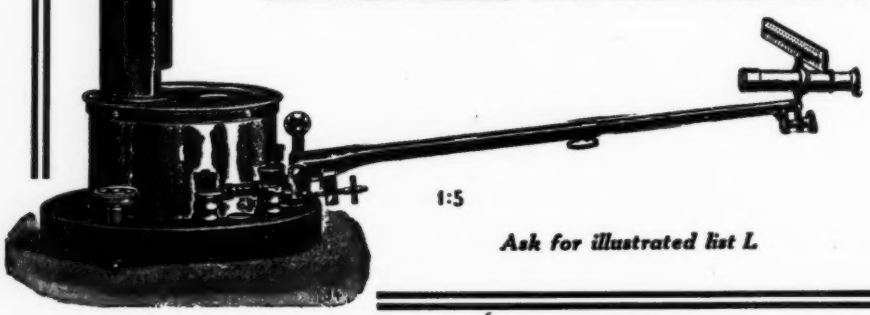
10 Curves of Sound Waves and Scheme together, $2.40

HARTMANN & BRAUN, A.-G.
FRANKFURT am Main (Germany)

Electrical Instruments for Laboratory Use

Galvanometers of all kinds for aperiodic and ballistic measurements

STANDARD RESISTANCES--STANDARD CELLS
POTENTIOMETERS--WHEATSTONE BRIDGES etc.



1:5

Ask for illustrated list L

Complete Line of Electrical Standard and Testing

Instruments

Including Precision Resistances, Rheostats, Reflecting Galvanometers, Potentiometers, Standard Wattmeters,

UNIPIVOT

Portable measuring instruments, from 10^{-7} ampere and 10^{-5} volt; for Direct, Alternating or High-Frequency Currents. Apparatus for High-Frequency

Measurement of Inductance, Capacity and Effective Resistance

20 YEARS' EUROPEAN REPUTATION

For Design and Workmanship

ROBT. W. PAUL

(HEAD OFFICE AND FACTORY, LONDON, ENGLAND)

1 EAST 42ND STREET, NEW YORK

New Wallace Replica Gratings

To our original line of replica gratings (made from Rowland gratings) we have added a new series (Nos. 3424 R and 3424 S) made from a **Michelson grating** of exceptional quality and ruled with 25000 lines to the inch. The great angular dispersion obtained by this number of lines makes the first order spectrum available for most work.

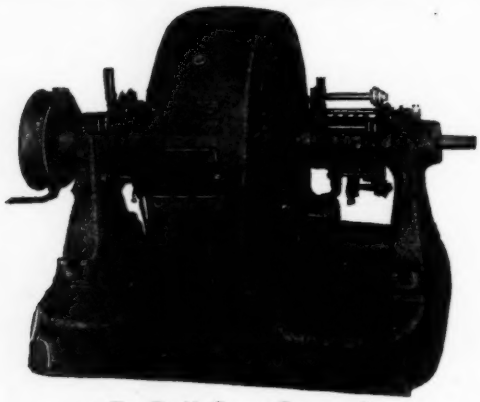
NET PRICE LIST

All Grade A and Grade B gratings are enclosed in leather covered velvet lined case.

No.	Size of Ruled Surface, mm.	Grade				No. of Lines to 1 Inch.
		A	B	C	D	
3420	28x20	$5.00	$4.00	$3.00	$2.00	14,438
3421	25x21	5.00	4.00	3.00	2.00	15,000
3422	28x20	5.00	4.00	3.00	2.00	20,000
3423	47x35	8.00	7.00	5.00	3.00	15,000
3424	46x32	8.00	7.00	5.00	3.00	20,000
3424R	25x30	6.00	5.00	4.00	2.50	25,000
3424S	50x30	10.00	8.00	6.00	4.00	25,000

CENTRAL SCIENTIFIC COMPANY

412 to 420 Orleans St. (Old Location) **CHICAGO, U. S. A.**



10 Kw. Double Current Generator Set

Electrical Machines

Especially Designed for Experimental Work in College Laboratories

Double Current Generator: Designed to illustrate the characteristics of the following machines.

Two-phase or three-phase synchronous converter.
Double current generator, giving direct current and single-phase, two-phase or three-phase alternating current.
Direct current generator.
Two-phase or three-phase alternating current generator.
Direct current motor.
Two-phase or three-phase synchronous motor.
Inverted synchronous converter giving two-phase or three-phase alternating current.

Polyphase Generator: Equipped with revolving field and three extra induction motor rotors. Illustrates the operating characteristics of generator, synchronous motor, and of squirrel cage, slip ring and internal resistance type induction motors.

Regulating Pole Converter: An 8 kw. machine that illustrates one of the more recent developments in synchronous motors.

General Electric Company

Largest Electrical Manufacturer in the World

General Office, Schenectady, N. Y. Sales Offices in fifty-four cities

4422

MORSE TWIST DRILL & MACHINE COMPANY New Bedford, Mass.

Makers of Twist Drills, Reamers, Cutters, Etc.

TOOLS THAT PROVE THEIR WORTH.

WM. GAERTNER & CO. 5345-49 Lake Avenue, CHICAGO.

PHYSICAL & ASTRONOMICAL APPARATUS

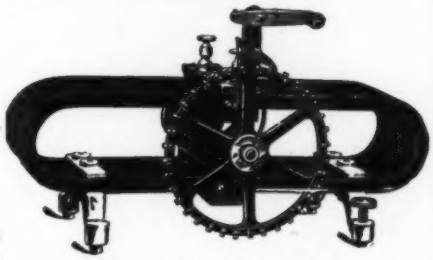
SPECIALTIES.

Interferometers, Cathetometers,

Spectrometers, Dividing Engines,

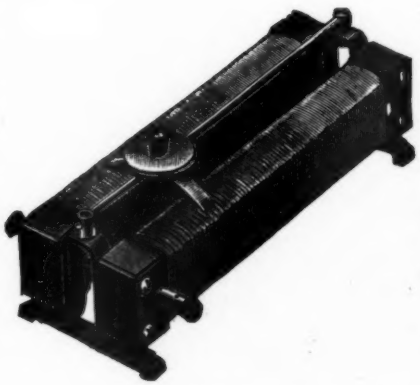
Heliostates, etc., etc.

We are now in position to furnish all the apparatus for MILLIKAN & MILL'S COURSE in Electricity, Sound and Light.



Dynamo Analysis Apparatus.

"G-R" Laboratory Rheostats



"G-R" Laboratory Rheostats, with sliding contacts, are extremely convenient for laboratory use. They are wound on slate blocks or enamelled steel tubes, and are furnished in several types, with current capacities and resistances enough in each type to suit almost every requirement. Used by Universities, Colleges, Industrial Companies, makers of Electrical Instruments, and Departments of the U. S. Government (including the Bureau of Standards).

For full particulars, write for new Illustrated Catalog 782.

JAMES G. BIDDLE

1211-13 Arch Street **PHILADELPHIA**

When in Philadelphia be sure to visit our Permanent Exhibit of Scientific Instruments

Franz Schmidt & Haensch

Scientific Instrument Makers

Berlin S. 42, Prinzessinnenstr. 16

Projection Apparatus for Diapositifs and Experiment, **Episcopes** and **Epidiascopes** of the newest perfect constructions, **Spectroscopes, Photometers, Polariscopes** of the highest sensibility for scientific work.

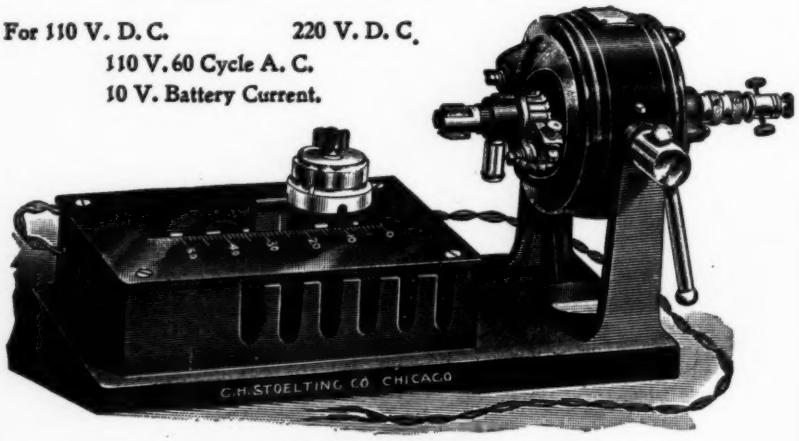
Prospectus on demand

New Episcopical Projection Apparatus

(Kugelepiskop D. R. P. No. 250314)

Electric Motor Rotators

For 110 V. D. C. 220 V. D. C.
110 V. 60 Cycle A. C.
10 V. Battery Current.



No. 803; 110 V. D. C.

C. H. STOELTING COMPANY

Scientific Apparatus and Laboratory Supplies

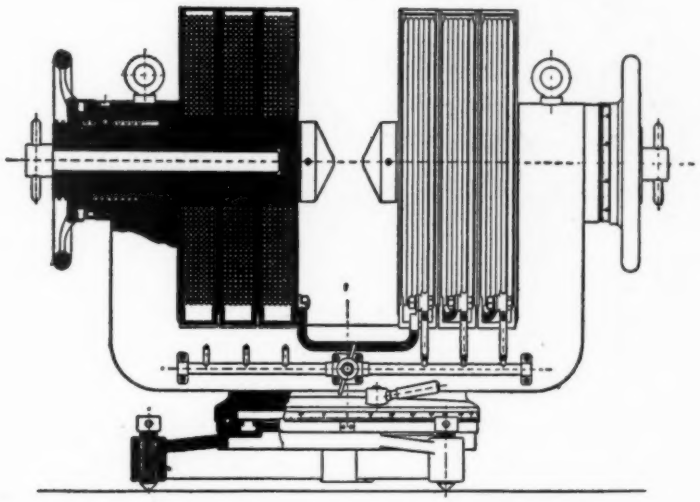
121 North Green St. CHICAGO, ILL., U. S. A.

Catalogue on Application

Société Genevoise pour la Construction d'Instruments de Physique et de Mécanique

GENEVA (Switzerland)

Makers of any Scientific Apparatus of Best Quality



New Design of Prof. P. WEISS Electromagnet.
(Patent)

Winding of coils with hollow copper tube, traversed by the electric current and the cooling water. Absolutely no heating of the magnet.

New Spectrometers and Spectrographs with great separating power (up to 55,800 units).

Measuring apparatus for Spectro Photograms. New design of highest accuracy.

Complete Equipments for Physical Laboratories

Write for an Illustrated Price List

The Bates Polariscope

Designed by Dr. Frederick Bates of the U. S. Bureau of Standards and manufactured for us by J. & J. Fric, of Prague, Bohemia. Bought by the U. S. Bureau of Standards for use as a Standard at Ports of Entry. Also in use by the U. S. Bureau of Chemistry.

Any desired sensibility and brightness obtainable without change of Zero point. For use with white light. The latest and most complete instrument on the market.

Full particulars upon application. A large line of other polariscopes for special or general purposes always in stock.

E. H. SARGENT & CO.

Established 1852

Importers, Makers and Dealers in Chemicals and Chemical Apparatus of High Grade only.

125-127 W. Lake Street CHICAGO

VOLUME II SECOND SERIES NUMBER 6

JAN 10 1914

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

734

CONDUCTED BY

THE AMERICAN PHYSICAL SOCIETY

BOARD OF EDITORS

F. BEDELL, Managing Editor

J. S. AMES W. F. MAGIE B. O. PEIRCE
K. E. GUTHE R. A. MILLIKAN C. A. SKINNER
J. C. McLENNAN E. F. NICHOLS J. ZELENY

DECEMBER, 1913

A Powerful Röntgen Ray Tube with a Pure Electron Discharge. W. D. COOLIDGE 409

The Change in the Elasticity of a Copper Wire with Current and External Heating. H. L. DODGE 431

The Effect of Space Charge and Residual Gases on Thermionic Currents in High Vacuum. IRVING LANGMUIR 450

The Sensibility Curves for Selenium; a New Sensibility-Wave-Length Maximum and a New Principle. F. C. BROWN and L. P. SIEG 487

On the Nature of the Volta Effect. FERNANDO SANFORD 495

The Magnetic Susceptibility of Gases. W. P. ROOP 497

Proceedings of the American Physical Society: 503
Conditions Involving a Decrease of Primary Current with Increasing Secondary Current, *F. J. Rogers;* Relativity Theory; General Dynamical Principles, *Richard C. Tolman;* Relativity Theory; the Equipartition Law in a System of Particles, *Richard C. Tolman.*

List of Members of the American Physical Society 507

Index 533

PUBLISHED BY
THE AMERICAN PHYSICAL SOCIETY
LANCASTER, PA., AND ITHACA, N. Y.

Entered at the post-office, at Lancaster, Pa., as second class matter

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

Conducted by

THE AMERICAN PHYSICAL SOCIETY

BOARD OF EDITORS

FREDERICK BEDELL, *Managing Editor*

J. S. AMES	W. F. MAGIE	B. O. PEIRCE
K. E. GUTHE	R. A. MILLIKAN	C. A. SKINNER
J. C. MCLENNAN	E. F NICHOLS	J. ZELENY

Annual Subscription, throughout the Postal Union, $6.00

Single Copies, postpaid, $.60

Subscriptions should be sent to THE PHYSICAL REVIEW, *41 North Queen Street, Lancaster, Pa., or Ithaca, N. Y.*

Two volumes of THE PHYSICAL REVIEW are published annually, these volumes beginning in January and July, respectively, and containing six numbers each.

A limited number of complete sets of the REVIEW, both First and Second Series, will be supplied at the price of $3.00 per volume for all volumes, carriage extra. When they can be furnished without breaking a set, separate back volumes will be supplied at the same price, and single back numbers will be mailed to any address in the Postal Union at the price of $.60 per copy.

First Series. From July 1, 1893, to January 1, 1913, the REVIEW was conducted by Edward L. Nichols, Ernest Merritt and Frederick Bedell, with the financial support of Cornell University. During this period thirty-five volumes were issued, constituting the First Series. The first four volumes of the First Series were issued annually; subsequent volumes were issued semi-annually.

Second Series. On January first, 1913, the Review was transferred to the American Physical Society. A second series was then begun, the January, 1913, number being designated Volume I., Number 1, Second Series. (An announcement of this transfer will be found on the first page of the new series.)

For advertising rates, address THE PHYSICAL REVIEW, *Ithaca, N. Y.* Change of copy in standing advertisements should be sent direct to the printers, THE NEW ERA PRINTING CO., *Lancaster, Pa.*

Contributors to the REVIEW are referred to page two of the advertisements for further information.

Permission is given to republish any article appearing in the REVIEW, provided proper credit is given.

Address correspondence to

THE PHYSICAL REVIEW, Ithaca, N. Y., U. S. A.

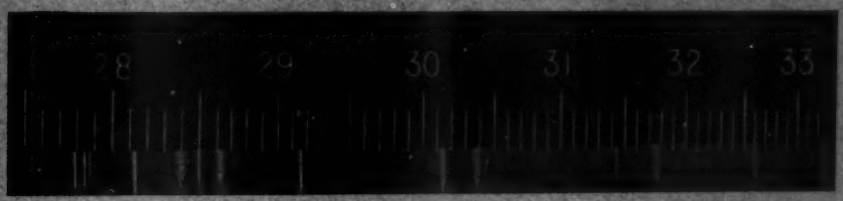
HILGER QUARTZ SPECTROGRAPH

Size C.

WITH WAVELENGTH SCALE

This Spectrograph, which is shown in the above illustration has quartz lenses of 610 mm. focal length, and gives a spectrum which measures 200 mm. from W. L. 2100 to W. L. 8000.

The following print is a process reproduction, enlarged three times, of a portion of a photograph of a comparison spectrum taken on one of these Spectrographs adapted with Wavelength Scale.



Full particulars post free on application to

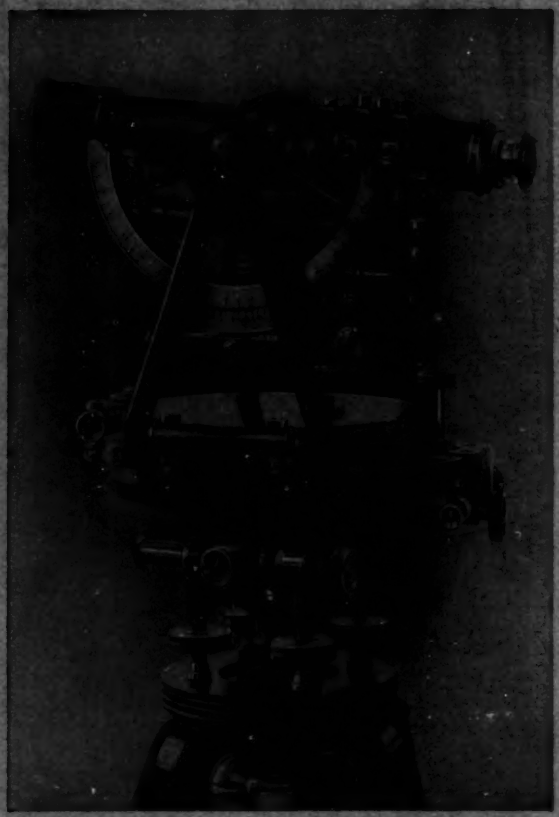
ADAM HILGER Ltd.

75 A. Camden Road **LONDON, N. W.**

Telegraphic address "Sphericity, London." Cable Code—Western Union.

W. & L. E. GURLEY

TROY, N. Y.



Manufacturers of
Civil Engineers and Surveyors Instruments,
Physical and Scientific Apparatus,
Standard Weights and Measures,
Mercurial Thermometers